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Title: Debugging Your Quantum Computation

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— EST. 1943 —

advanced network
science initiative
(ansi)

Debugging Your Quantum Computation

Carleton Coffrin

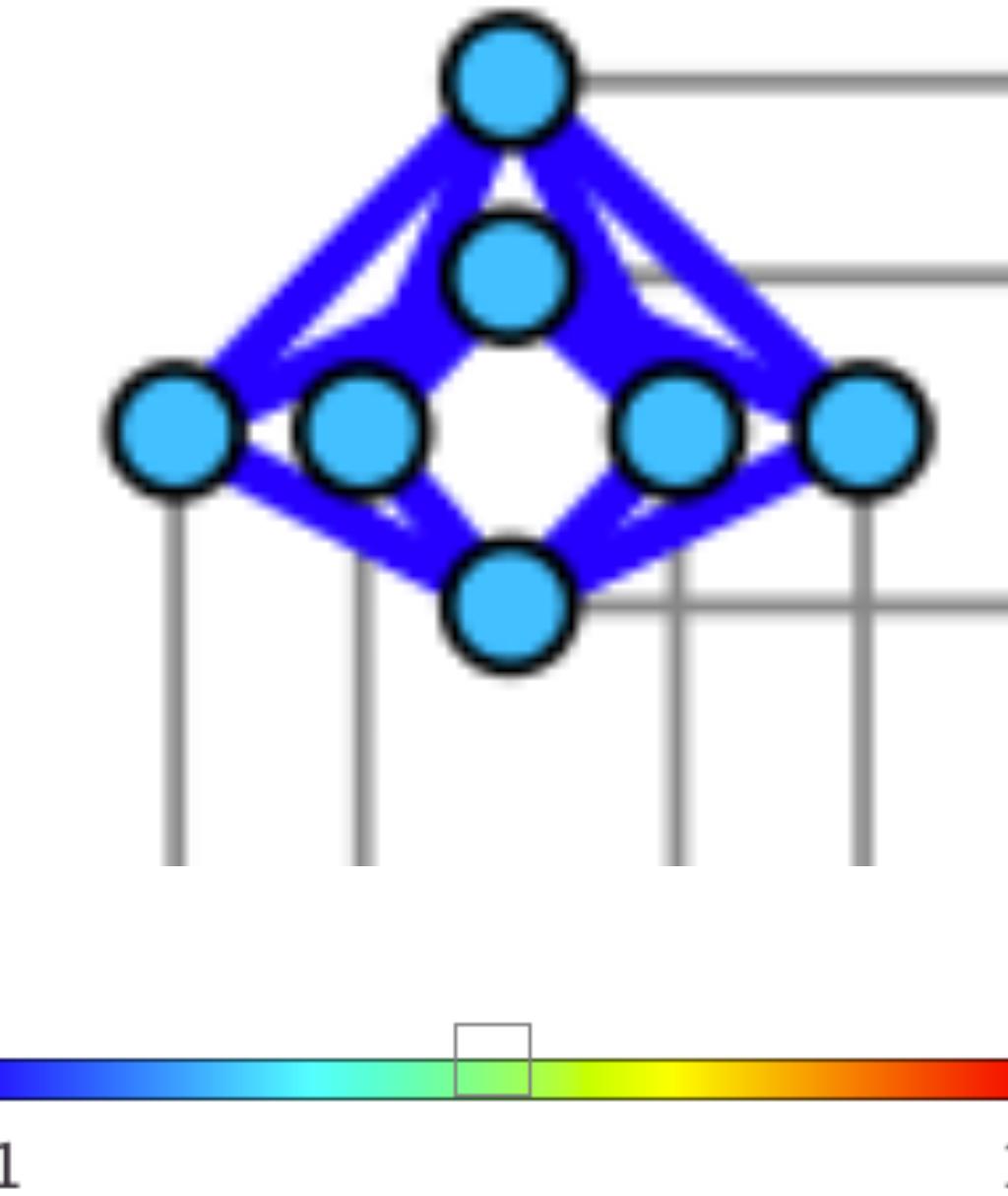
A-1

Debugging Approach

- Handcraft **very small** examples
- Know the “**correct**” answer for the example
 - **Optimization** - compute global minimum
 - **Sampling** - enumerate all states and compute partition function
- Some examples, from **my experience**

All Negative Example

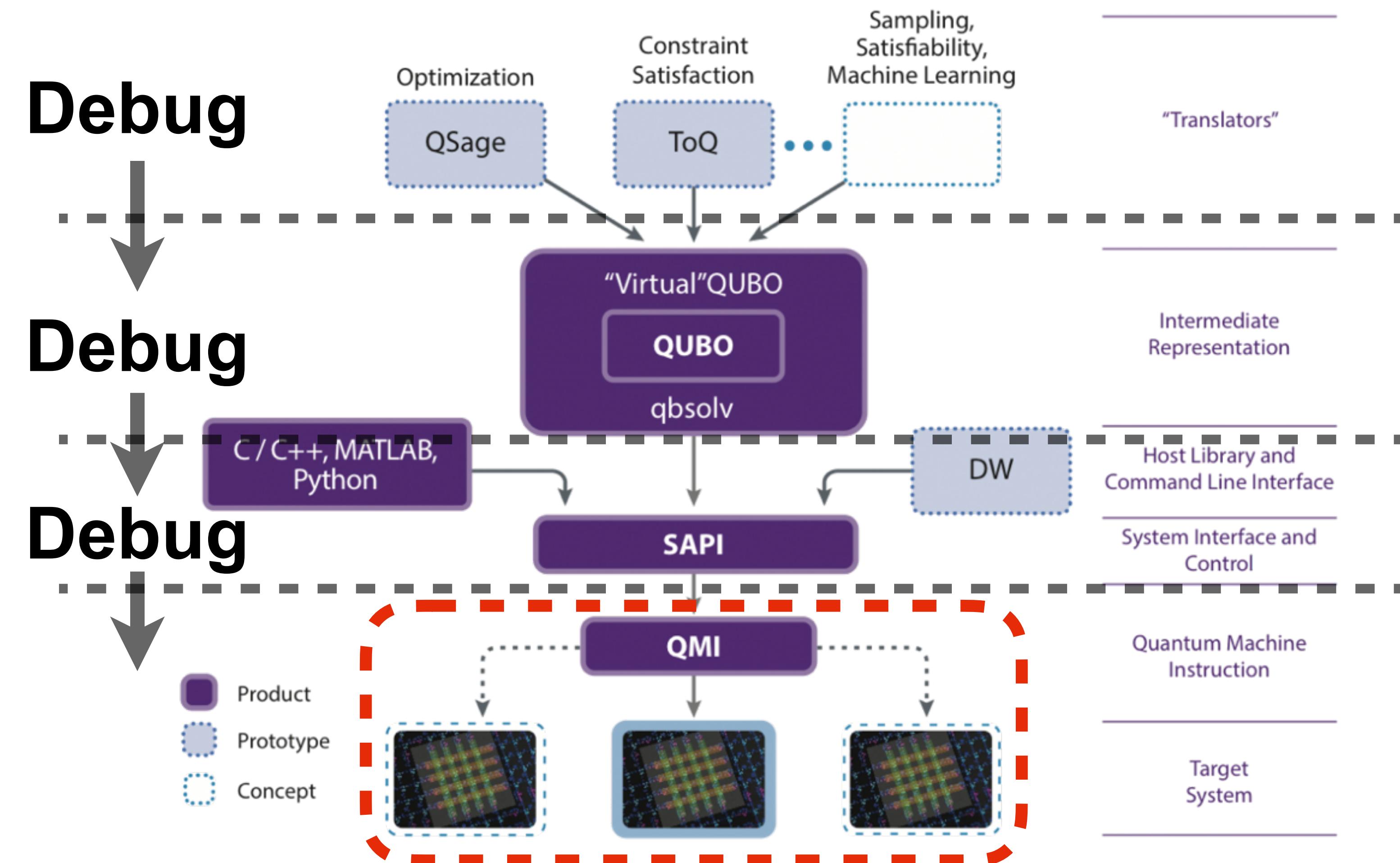
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6 19
0 0 -1.0
1 1 -1.0
2 2 -1.0
3 3 -1.0
4 4 -1.0
5 5 -1.0
6 6 -1.0
2 6 -1.0
0 6 -1.0
1 4 -1.0
1 5 -1.0
0 5 -1.0
3 6 -1.0
0 4 -1.0
1 6 -1.0
2 5 -1.0
3 4 -1.0
2 4 -1.0
3 5 -1.0
```



Known Properties

- Unique global optimum
- [1,1,1,1,1,1,1]
- Energy Value -19

Debugging Approach



Debugging Approach

Problem Status

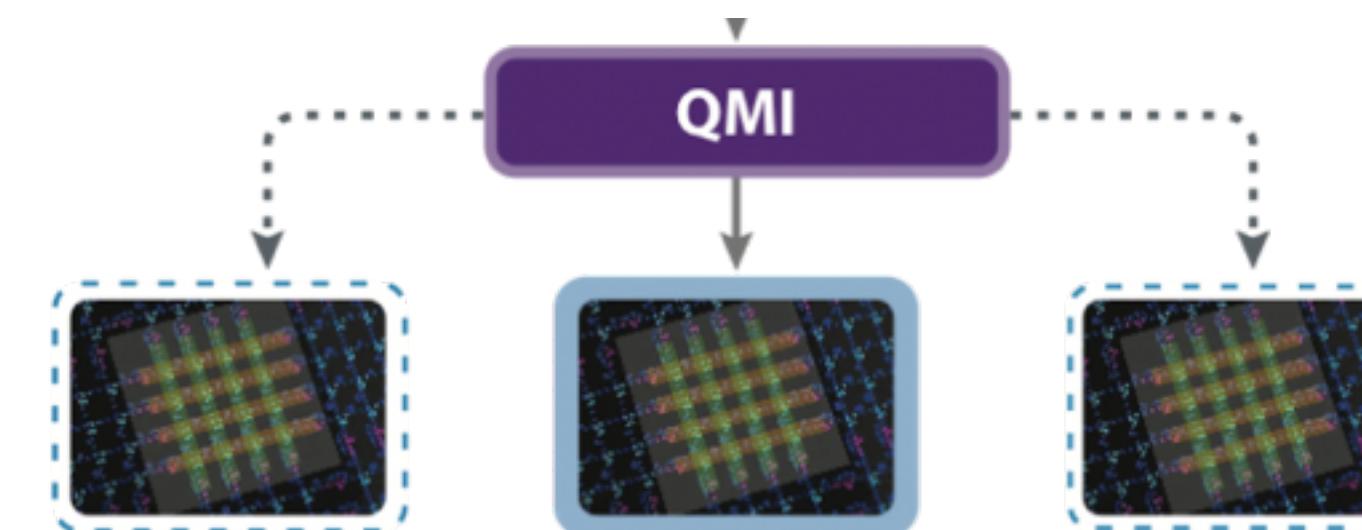
?

Show 10 entries

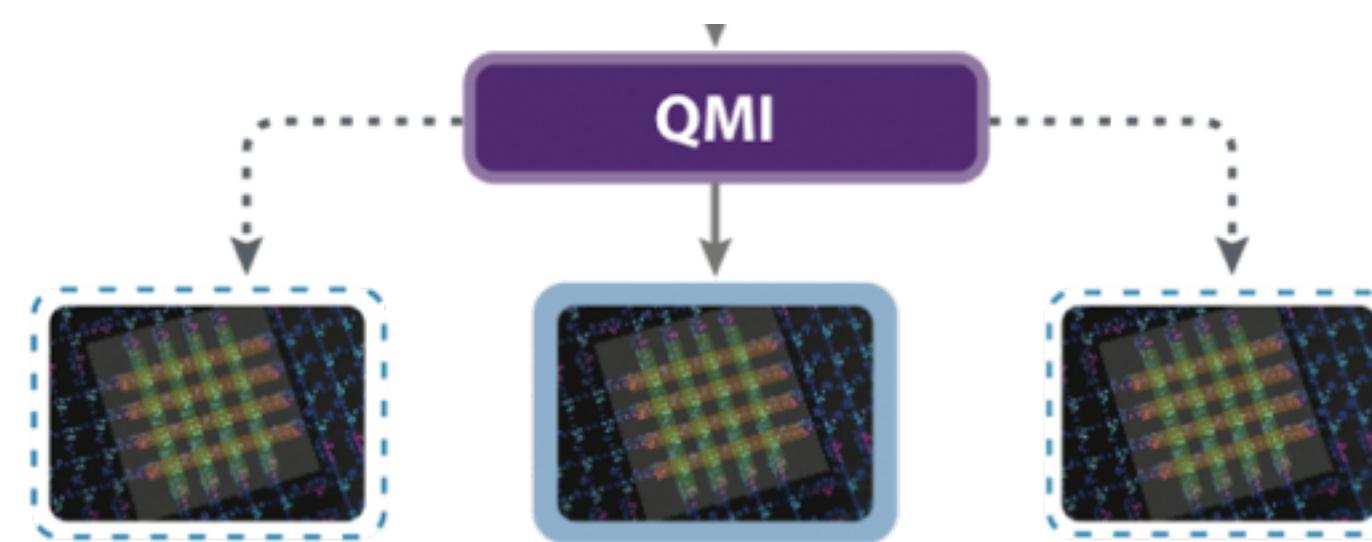
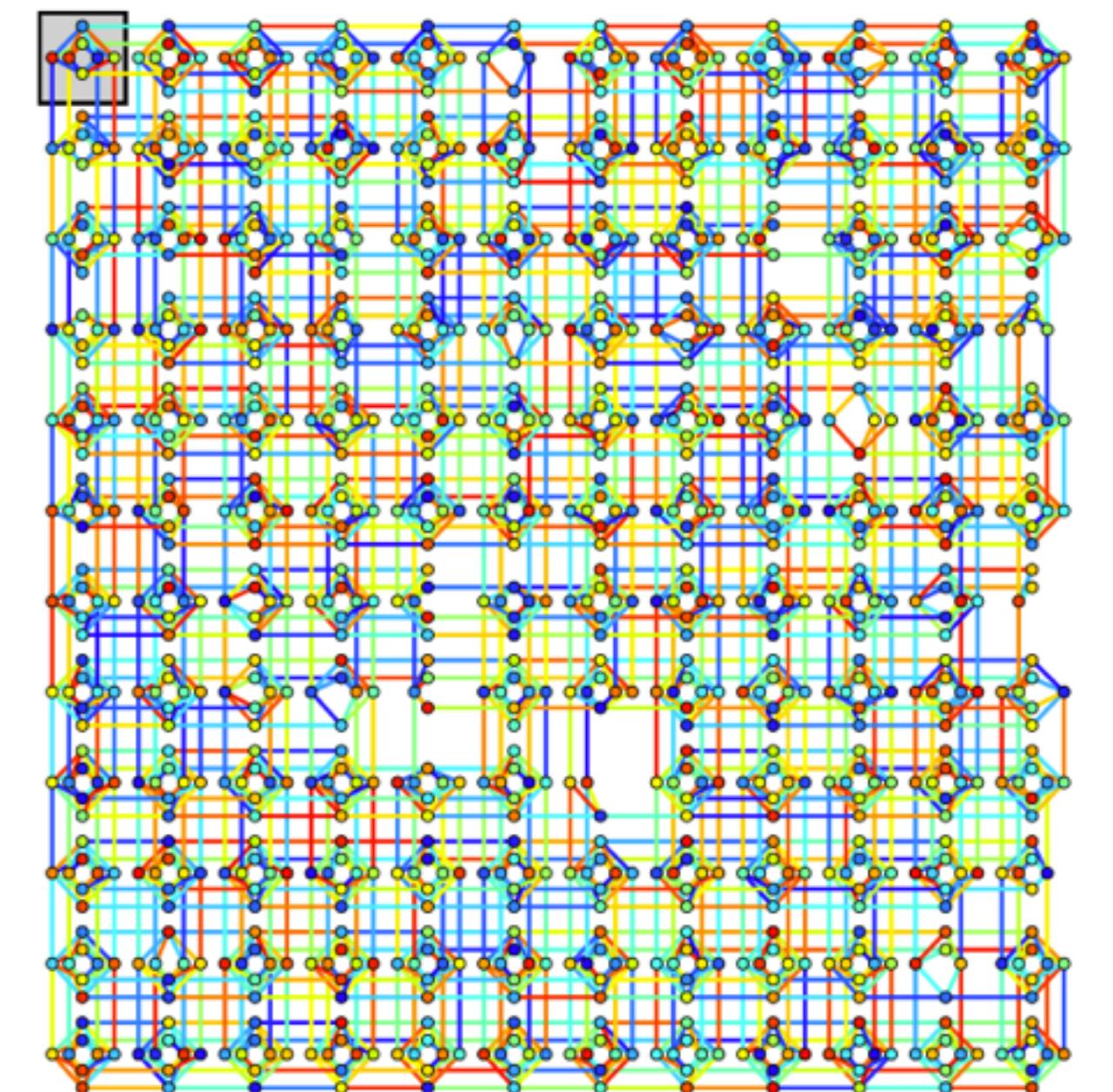
Filter problems Cancel Problems

Search for ID or Api Key

ID	Time Received	Time Solved	Status	Solver	Api Key	User
8e279f4f-0f59-4b65-... [REDACTED]	2017-02-02 11:53:23	2017-02-02 11:53:23	COMPLETED	DW2X	LANL-1c2e43d54fb9... [REDACTED]	cjc@lanl.gov
c33a33c5-1e2b-4548-... [REDACTED]	2017-02-02 11:53:03	2017-02-02 11:53:03	COMPLETED	DW2X	LANL-1c2e43d54fb9... [REDACTED]	cjc@lanl.gov
ef8bf49e-4cdf-4253-a... [REDACTED]	2017-01-26 19:07:25	2017-01-26 19:07:26	COMPLETED	DW2X	LANL-1c2e43d54fb9... [REDACTED]	cjc@lanl.gov

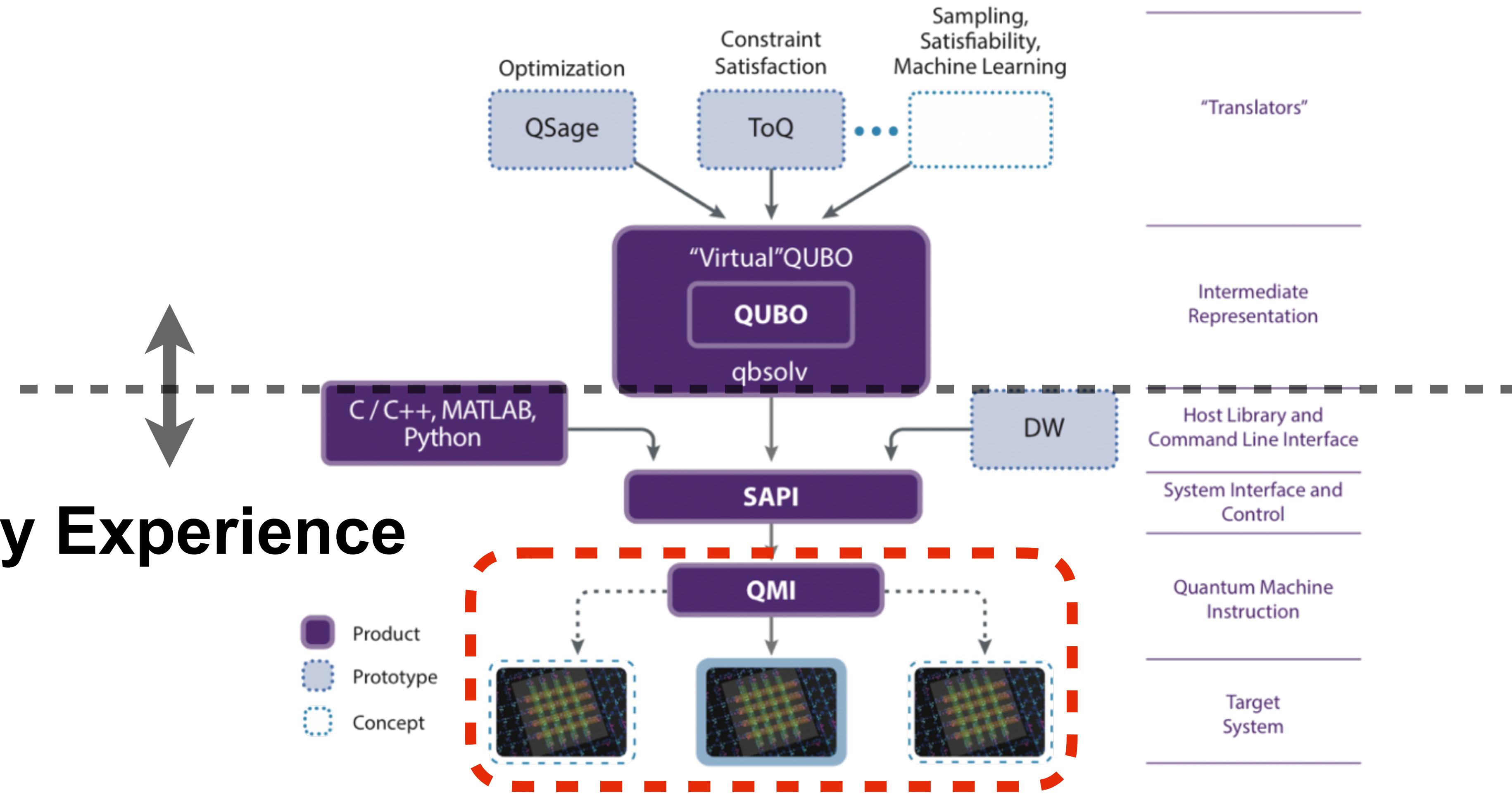


Debugging Approach

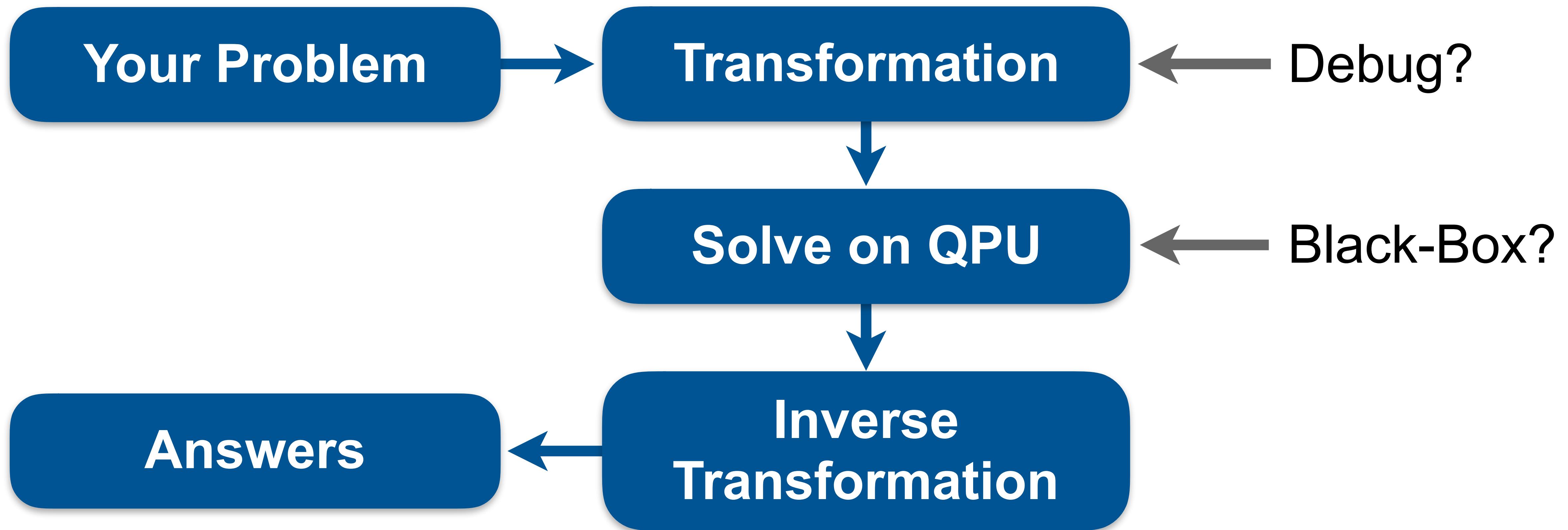


Oh really?

Debugging Approach

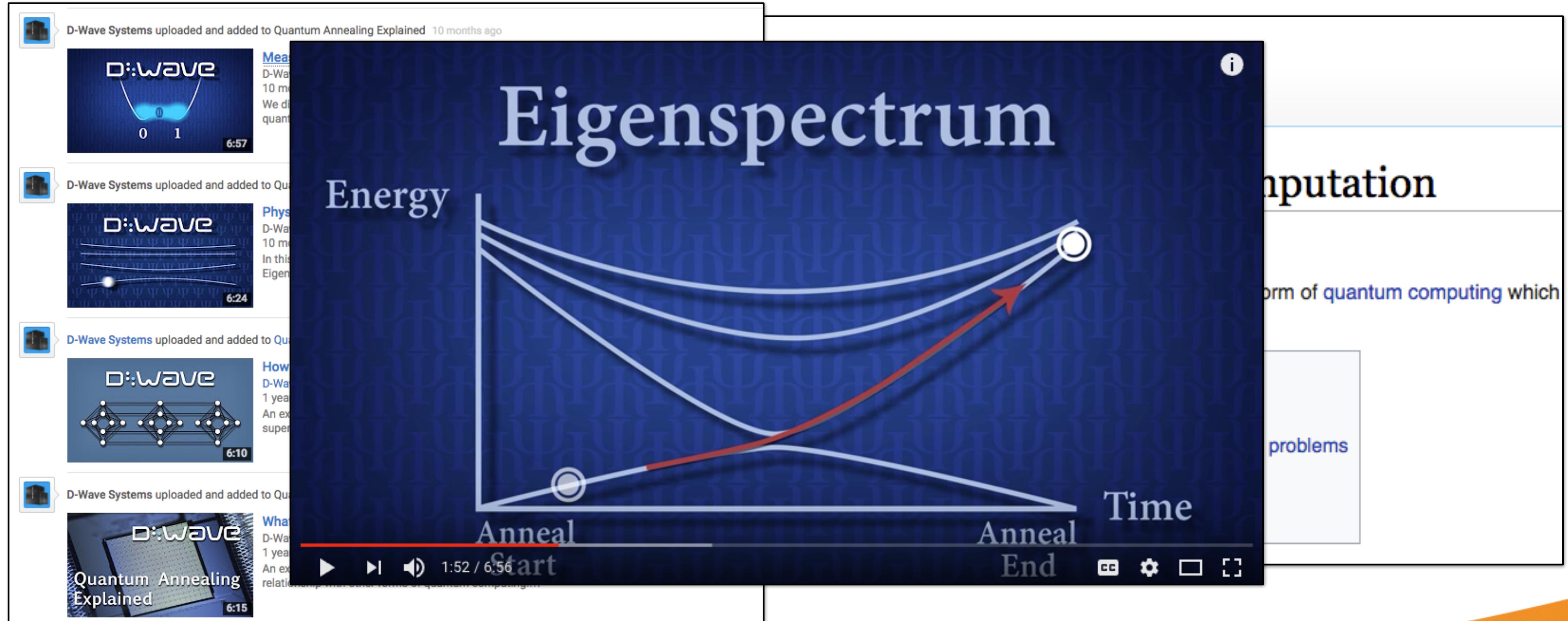


Many Quantum Computation Workflows



What do you expect the QPU to do?

What is Adiabatic Quantum Computation?

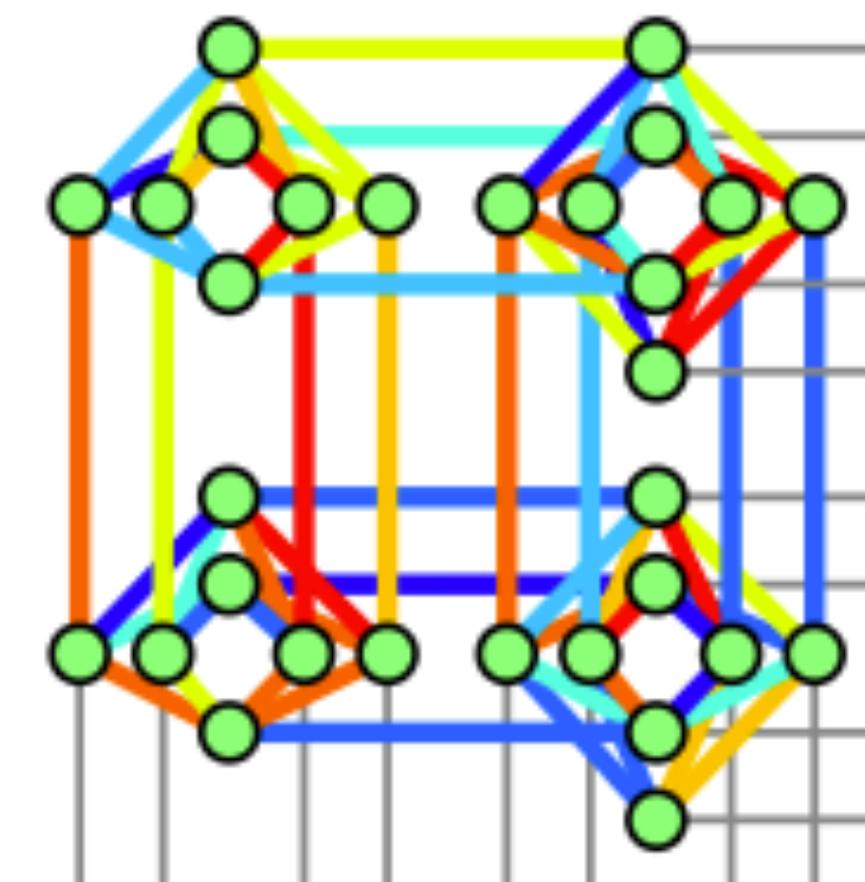


What did I learn about AQC?

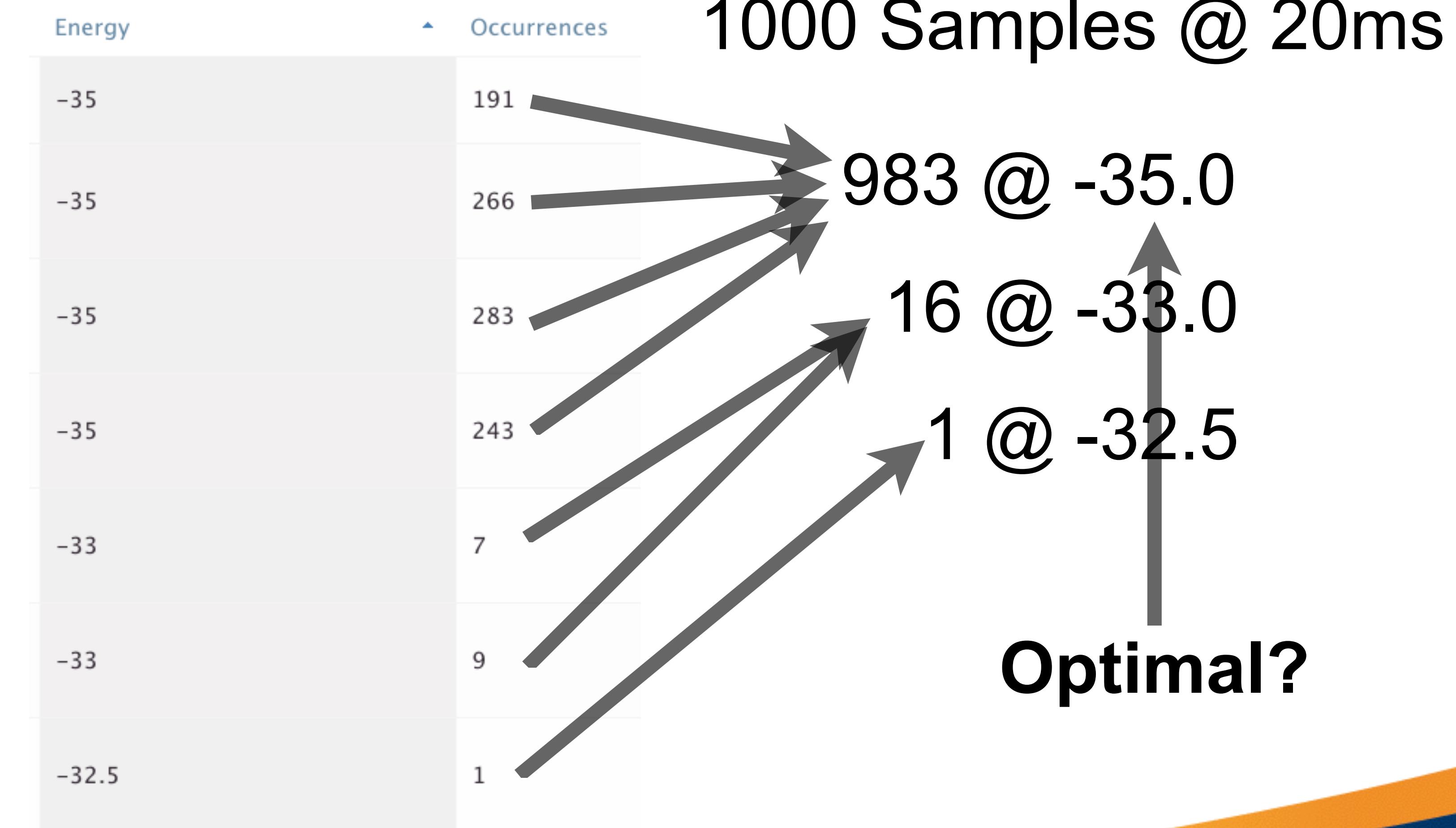
- It's all about **global optimality / ground state**
- If you **anneal slow enough**, you will get the best answer

Lets test it!

Chimera Degree 2, RAN4 (D-WIG)



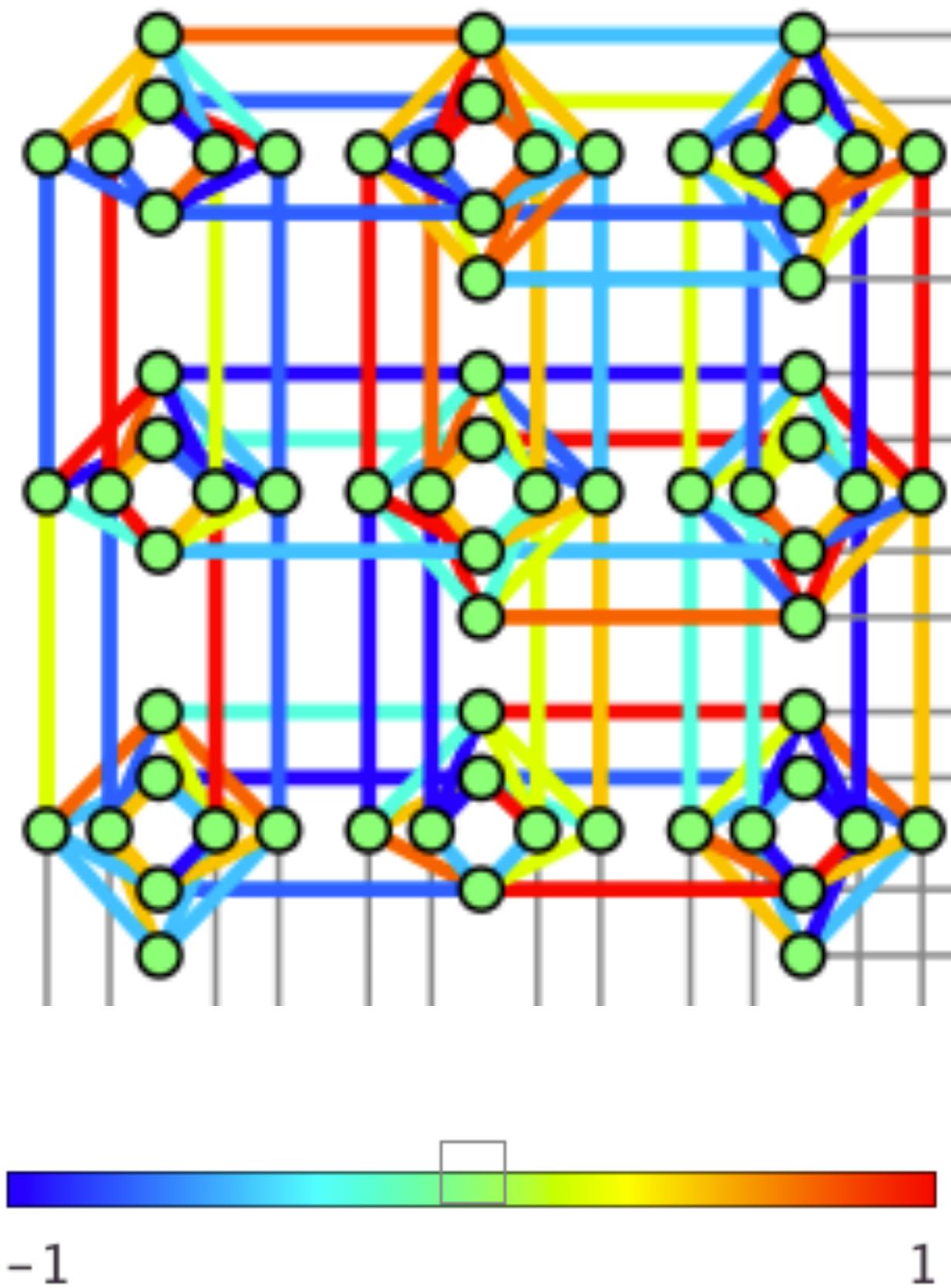
-1 1



Chimera Degree 2, RAN4

1152 70	0 96 0.75	105 110 0.75
0 4 -0.5	1 97 0.25	106 110 -1
1 4 0.25	2 98 1	107 110 -0.25
2 4 0.5	3 99 0.5	104 111 -0.75
3 4 0.25	96 100 -1	105 111 -0.75
0 5 -1	97 100 -0.25	106 111 0.5
1 5 0.5	98 100 0.75	107 111 0.5
2 5 1	99 100 1	
3 5 0.25	96 101 -0.25	
0 6 -0.5	97 101 -0.75	
1 6 -0.5	98 101 -0.75	
2 6 1	99 101 0.75	
3 6 0.25	96 102 0.75	
4 12 0.25	97 102 0.25	
8 12 -1	98 102 0.75	
9 12 -0.5	99 102 0.75	
10 12 -0.25	8 104 0.75	
11 12 0.25	9 105 -0.5	
5 13 -0.25	10 106 -0.75	
8 13 0.75	11 107 -0.75	
9 13 -0.75	100 108 -0.75	
10 13 0.75	104 108 -0.5	
11 13 1	105 108 0.5	
6 14 -0.5	106 108 1	
8 14 0.75	107 108 0.25	
9 14 -0.25	101 109 -1	
10 14 1	104 109 0.75	
11 14 0.25	105 109 1	
8 15 0.25	106 109 -1	
9 15 -1	107 109 -0.75	
10 15 1	102 110 -0.75	
11 15 1	104 110 -0.25	

Chimera Degree 3, RAN4



Energy	Occurrences
-73.25	2
-73.25	1
-73.25	1
-73.25	5
-73.25	1
-72.75	2
-72.75	69
-72.75	10
-72.75	203

1000 Samples @ 20ms

10 @ -73.25

>700 @ -72.75

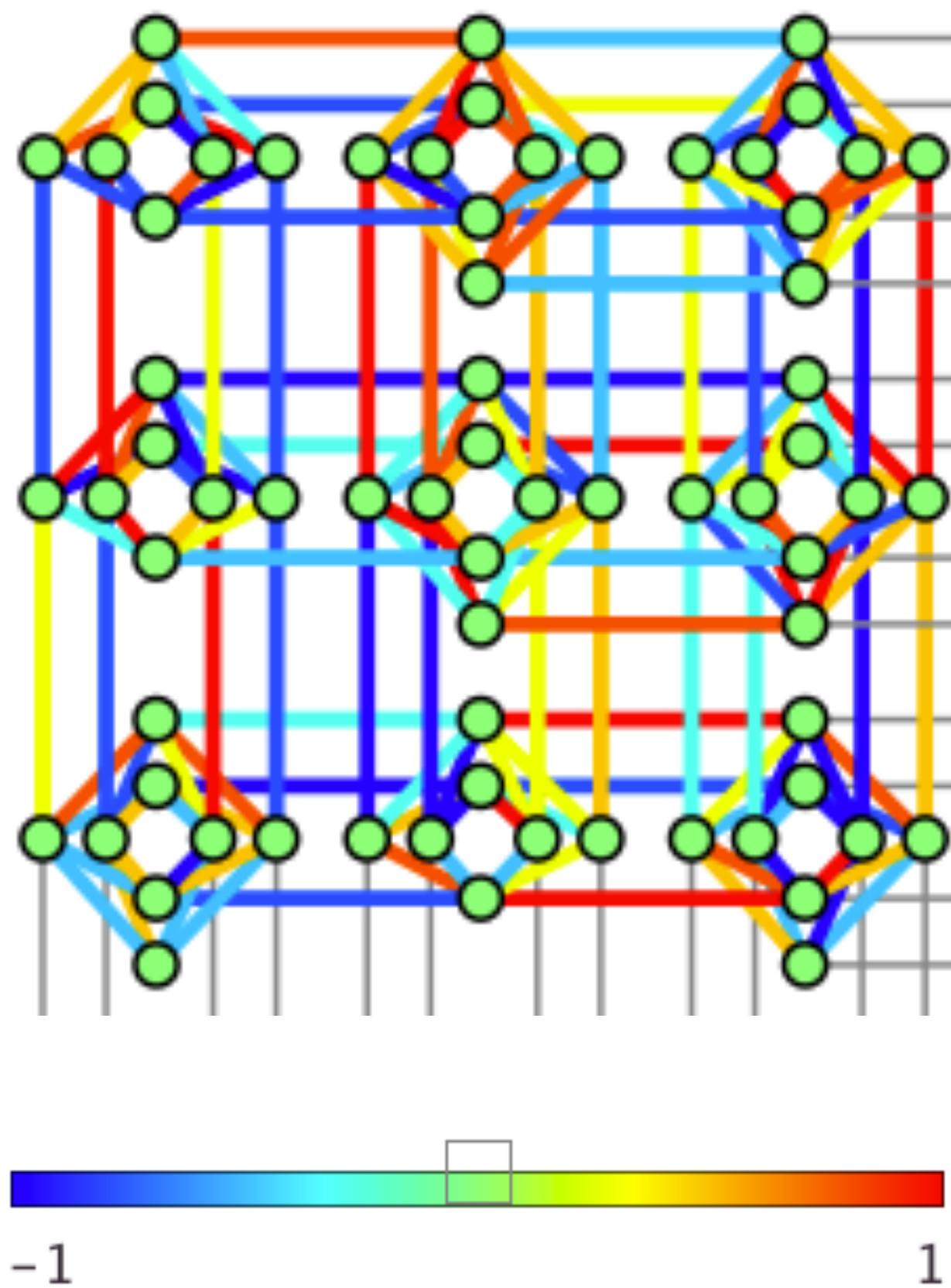
300 @ higher-energy

Numerical Issue?

Chimera Degree 3, RAN4

1152 176	12 20 -0.5	96 102 -0.25	112 116 -0.5	193 198 0.5	209 212 -1
0 4 0.5	16 20 -0.5	97 102 1	113 116 0.25	194 198 -1	210 212 -1
1 4 0.5	17 20 0.75	98 102 0.5	114 116 -0.25	195 198 0.5	211 212 0.75
2 4 -0.5	18 20 -1	99 102 0.25	115 116 1	192 199 -0.5	205 213 -0.75
3 4 -0.25	19 20 0.5	8 104 1	109 117 1	193 199 0.5	208 213 -0.5
0 5 0.75	13 21 0.25	9 105 0.75	112 117 0.25	194 199 -0.5	209 213 -0.5
1 5 0.25	16 21 -0.75	10 106 0.5	113 117 0.25	195 199 -0.5	210 213 -1
2 5 -1	17 21 -1	11 107 -0.5	114 117 -0.5	104 200 -1	211 213 -0.75
3 5 1	18 21 -0.25	100 108 -1	115 117 0.5	105 201 -1	206 214 1
0 6 -0.75	19 21 0.5	104 108 -0.25	110 118 -0.5	106 202 0.25	208 214 0.75
1 6 -0.75	14 22 -0.75	105 108 0.75	112 118 -0.25	107 203 0.5	209 214 -1
2 6 0.75	16 22 0.25	106 108 0.25	113 118 0.75	196 204 -0.25	210 214 1
3 6 -1	17 22 1	107 108 -0.75	114 118 0.5	200 204 -0.25	211 214 0.5
4 12 0.75	18 22 0.75	101 109 -0.25	115 118 -0.75	201 204 -1	208 215 0.5
8 12 0.5	19 22 0.75	104 109 -0.5	111 119 0.75	202 204 0.25	209 215 -0.5
9 12 1	15 23 -0.5	105 109 0.5	112 119 -0.75	203 204 0.25	210 215 -1
10 12 0.75	16 23 -0.5	106 109 -0.25	113 119 1	197 205 -1	211 215 -0.5
11 12 0.5	17 23 -0.75	107 109 -0.75	114 119 1	200 205 0.5	
5 13 -0.75	18 23 0.5	102 110 -0.5	115 119 0.5	201 205 -1	
8 13 -0.75	19 23 0.25	104 110 1	96 192 0.25	202 205 1	
9 13 1	0 96 -0.75	105 110 0.5	97 193 -0.75	203 205 -0.25	
10 13 0.75	1 97 1	106 110 -0.25	98 194 1	198 206 -0.75	
11 13 -0.25	2 98 0.25	107 110 0.5	99 195 -0.75	200 206 0.75	
6 14 -0.75	3 99 -0.75	104 111 -0.25	192 196 0.75	201 206 -0.5	
8 14 -1	96 100 1	105 111 1	193 196 -0.75	202 206 -0.5	
9 14 -0.75	97 100 0.75	106 111 -0.25	194 196 0.25	203 206 0.25	
10 14 0.75	98 100 -1	107 111 0.25	195 196 0.75	112 208 -0.25	
11 14 -0.5	99 100 -0.5	16 112 0.25	192 197 -0.5	113 209 -0.25	
8 15 0.5	96 101 -1	17 113 -0.75	193 197 0.5	114 210 -1	
9 15 0.25	97 101 0.5	18 114 -1	194 197 -0.5	115 211 0.5	
10 15 0.75	98 101 -0.75	19 115 1	195 197 0.5	204 212 1	
11 15 0.75	99 101 -1	108 116 -1	192 198 -0.5	208 212 0.25	

Chimera Degree 3, RAN4 (rounded)



$$\begin{array}{l} 0.75 \rightarrow 0.8 \\ 0.25 \rightarrow 0.3 \end{array}$$

Energy	Occurrences
-75.3	2
-75.3	9
-75.1	3
-74.9	1
-74.7	1
-74.7	4
-74.7	3
-74.7	4
-74.7	1
-74.5	1

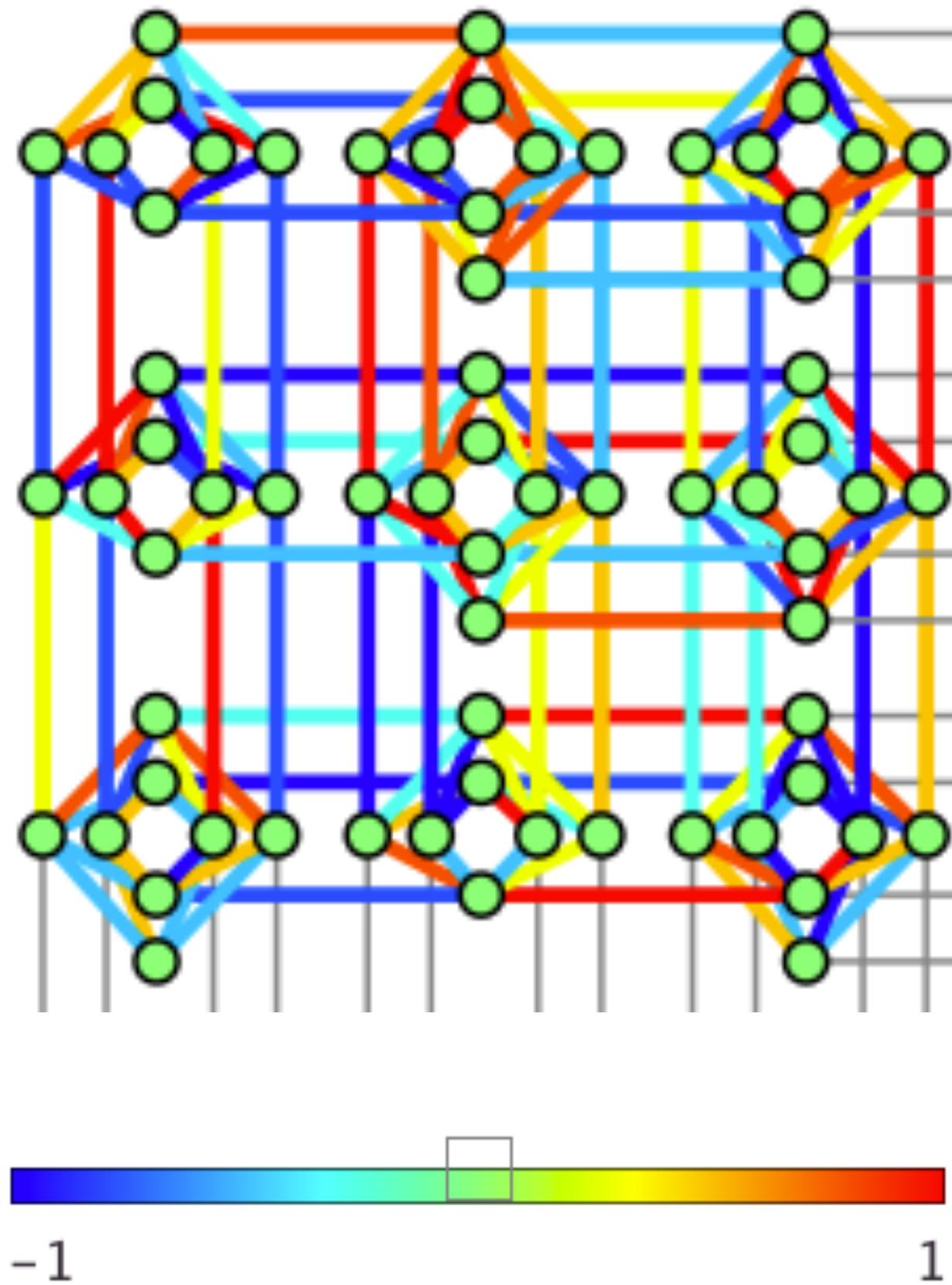
1000 Samples @ 20ms

11 @ -75.3
3 @ -75.1
1 @ -74.9
12 @ -74.7
>400 @ -74.5

Increase Anneal Time!

Seem less like a numerical issue...

Chimera Degree 3, RAN4 (rounded)



$0.75 \rightarrow 0.8$
 $0.25 \rightarrow 0.3$

Energy	Occurrences
-75.3	6
-75.3	8
-75.1	3
-75.1	2
-74.7	1
-74.7	2
-74.7	5
-74.7	3
-74.5	2
-74.5	1

500 Samples @ 2000ms

14 @ -75.3

5 @ -75.1

0 @ -74.9

14 @ -74.7

>250 @ -74.5

What
Changed?

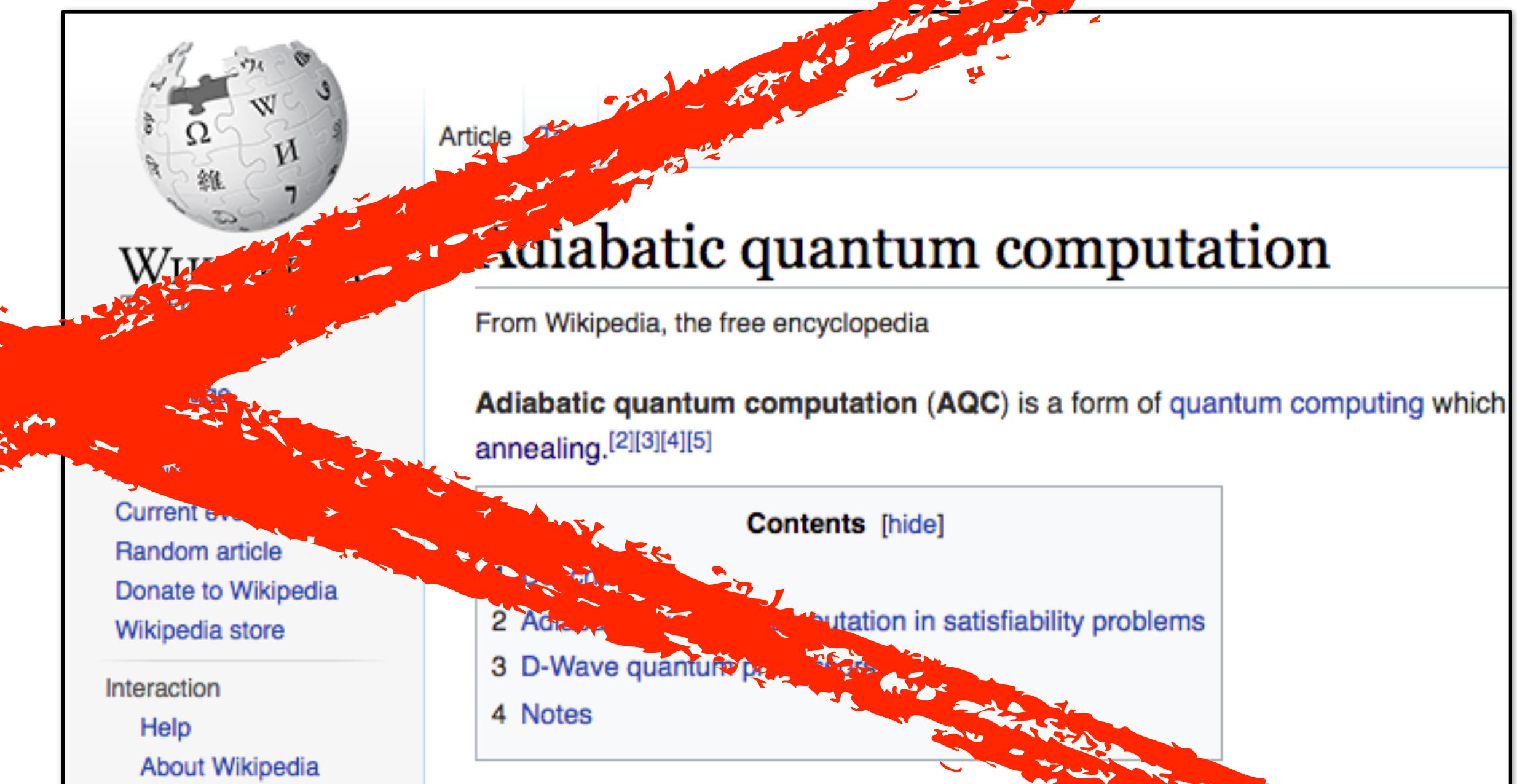
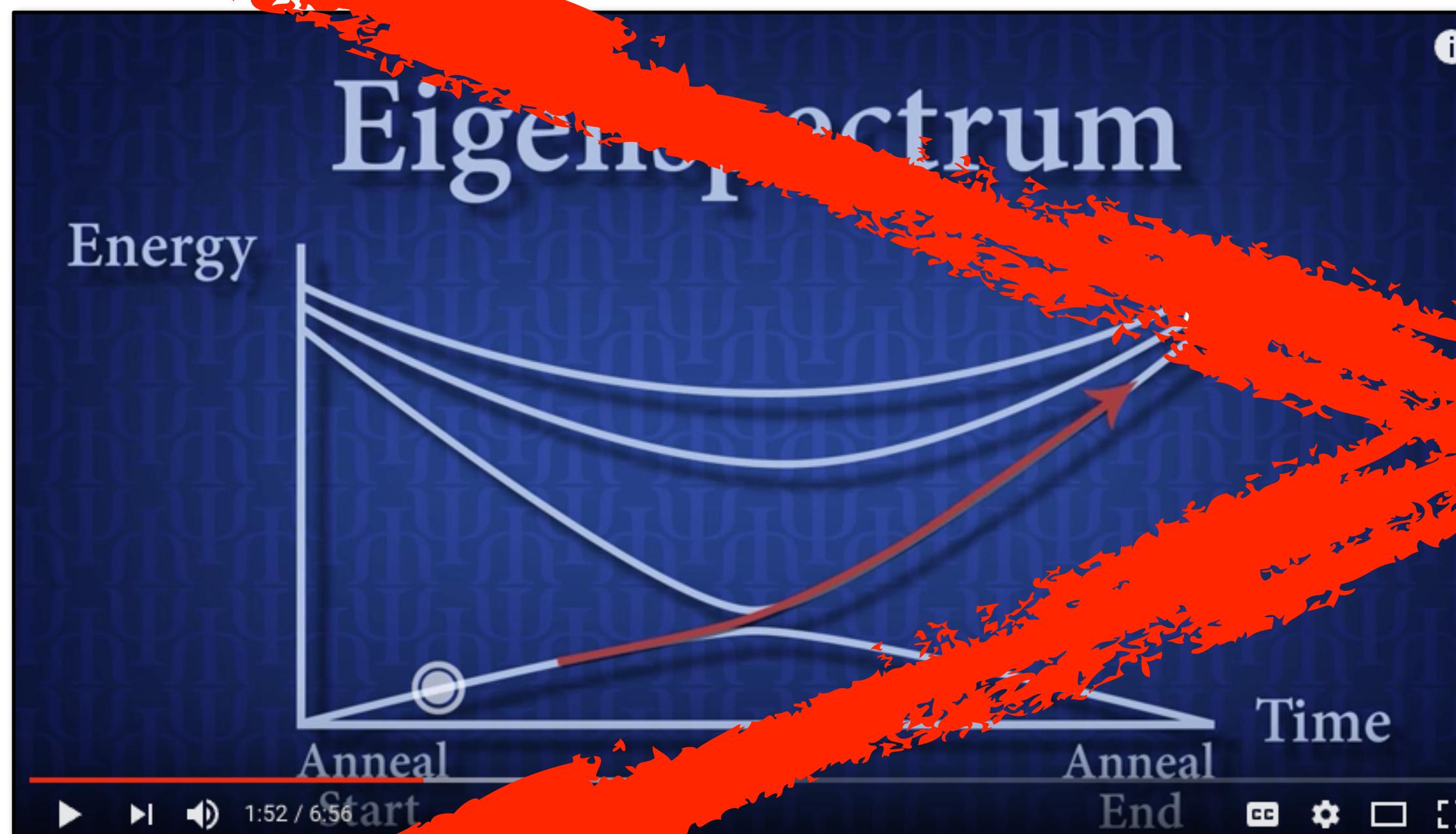
NOT
MUCH!

Chimera Degree 3, RAN4 (rounded)

1152 176	12 20 -0.5	96 102 -0.3	112 116 -0.5	193 198 0.5	209 212 -1
0 4 0.5	16 20 -0.5	97 102 1	113 116 0.3	194 198 -1	210 212 -1
1 4 0.5	17 20 0.8	98 102 0.5	114 116 -0.3	195 198 0.5	211 212 0.8
2 4 -0.5	18 20 -1	99 102 0.3	115 116 1	192 199 -0.5	205 213 -0.8
3 4 -0.3	19 20 0.5	8 104 1	109 117 1	193 199 0.5	208 213 -0.5
0 5 0.8	13 21 0.3	9 105 0.8	112 117 0.3	194 199 -0.5	209 213 -0.5
1 5 0.3	16 21 -0.8	10 106 0.5	113 117 0.3	195 199 -0.5	210 213 -1
2 5 -1	17 21 -1	11 107 -0.5	114 117 -0.5	104 200 -1	211 213 -0.8
3 5 1	18 21 -0.3	100 108 -1	115 117 0.5	105 201 -1	206 214 1
0 6 -0.8	19 21 0.5	104 108 -0.3	110 118 -0.5	106 202 0.3	208 214 0.8
1 6 -0.8	14 22 -0.8	105 108 0.8	112 118 -0.3	107 203 0.5	209 214 -1
2 6 0.8	16 22 0.3	106 108 0.3	113 118 0.8	196 204 -0.3	210 214 1
3 6 -1	17 22 1	107 108 -0.8	114 118 0.5	200 204 -0.3	211 214 0.5
4 12 0.8	18 22 0.8	101 109 -0.3	115 118 -0.8	201 204 -1	208 215 0.5
8 12 0.5	19 22 0.8	104 109 -0.5	111 119 0.8	202 204 0.3	209 215 -0.5
9 12 1	15 23 -0.5	105 109 0.5	112 119 -0.8	203 204 0.3	210 215 -1
10 12 0.8	16 23 -0.5	106 109 -0.3	113 119 1	197 205 -1	211 215 -0.5
11 12 0.5	17 23 -0.8	107 109 -0.8	114 119 1	200 205 0.5	
5 13 -0.8	18 23 0.5	102 110 -0.5	115 119 0.5	201 205 -1	
8 13 -0.8	19 23 0.3	104 110 1	96 192 0.3	202 205 1	
9 13 1	0 96 -0.8	105 110 0.5	97 193 -0.8	203 205 -0.3	
10 13 0.8	1 97 1	106 110 -0.3	98 194 1	198 206 -0.8	
11 13 -0.3	2 98 0.3	107 110 0.5	99 195 -0.8	200 206 0.8	
6 14 -0.8	3 99 -0.8	104 111 -0.3	192 196 0.8	201 206 -0.5	
8 14 -1	96 100 1	105 111 1	193 196 -0.8	202 206 -0.5	
9 14 -0.8	97 100 0.8	106 111 -0.3	194 196 0.3	203 206 0.3	
10 14 0.8	98 100 -1	107 111 0.3	195 196 0.8	112 208 -0.3	
11 14 -0.5	99 100 -0.5	16 112 0.3	192 197 -0.5	113 209 -0.3	
8 15 0.5	96 101 -1	17 113 -0.8	193 197 0.5	114 210 -1	
9 15 0.3	97 101 0.5	18 114 -1	194 197 -0.5	115 211 0.5	
10 15 0.8	98 101 -0.8	19 115 1	195 197 0.5	204 212 1	
11 15 0.8	99 101 -1	108 116 -1	192 198 -0.5	208 212 0.3	

What to expect from the QPU

How I think about the QPU



How I think about the QPU

- It is not an optimization tool, striving for global optimality / ground state
- It is more like a sampler from a Boltzmann/Gibbs-like distribution

$$\sigma \in \{-1, 1\} \quad J, h$$

$$\beta \approx 6.0 \pm 1.0 \quad p_\sigma = \frac{1}{Z} e^{-\beta \left(\sum_{i,j \in \mathcal{E}} J_{ij} \sigma_i \sigma_j + \sum_{i \in \mathcal{N}} h_i \sigma_i \right)}$$

Andrey Lokhov (T-4)

How I think about the QPU

- Good News!
- Sampling from Boltzmann is like a probabilistic optimization algorithm

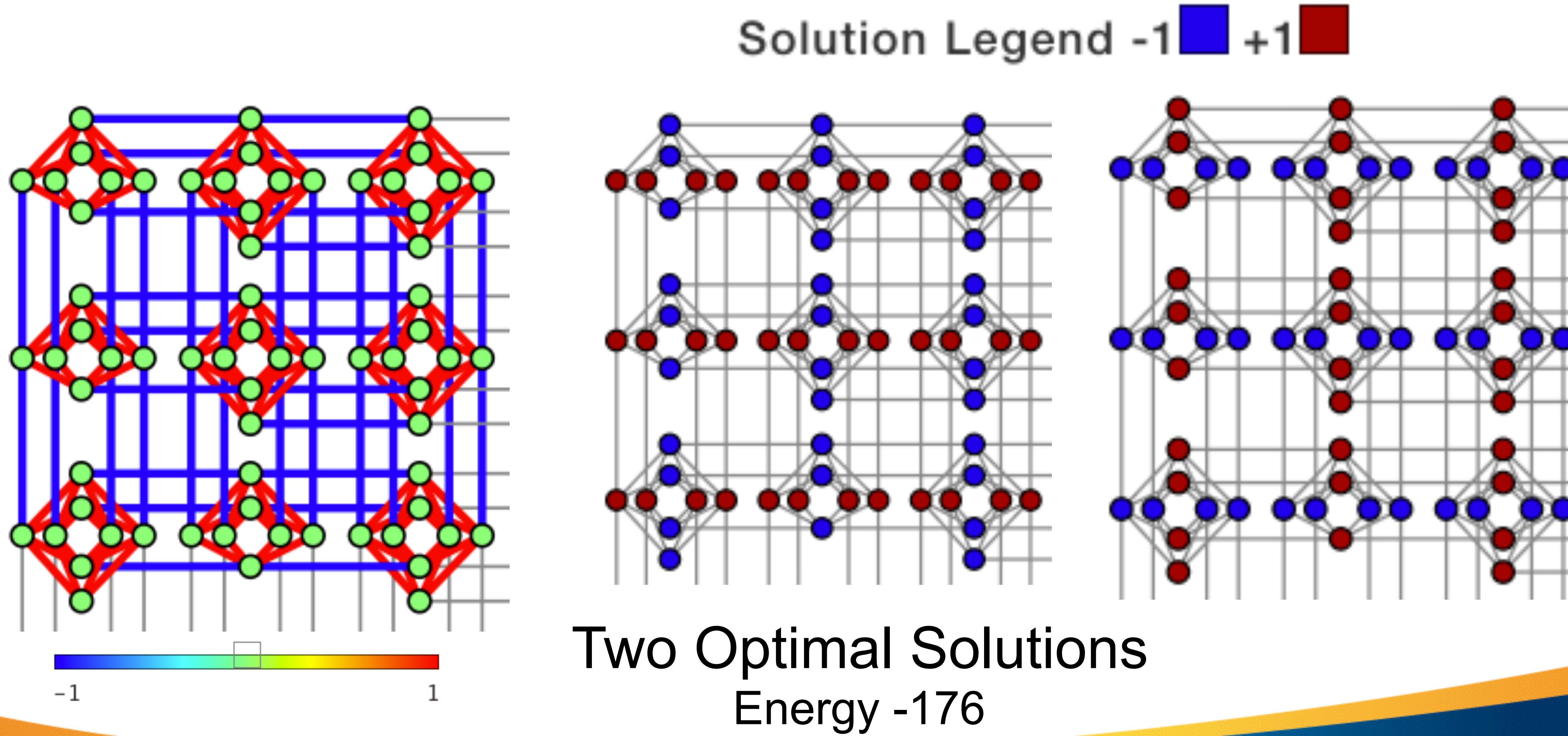
Lets test it!

$$\sigma \in \{-1, 1\} \quad J, h$$

$$\beta \approx 6.0 \pm 1.0 \quad p_\sigma = \frac{1}{Z} e^{-\beta \left(\sum_{i,j \in \mathcal{E}} J_{ij} \sigma_i \sigma_j + \sum_{i \in \mathcal{N}} h_i \sigma_i \right)}$$

Andrey Lokhov (T-4)

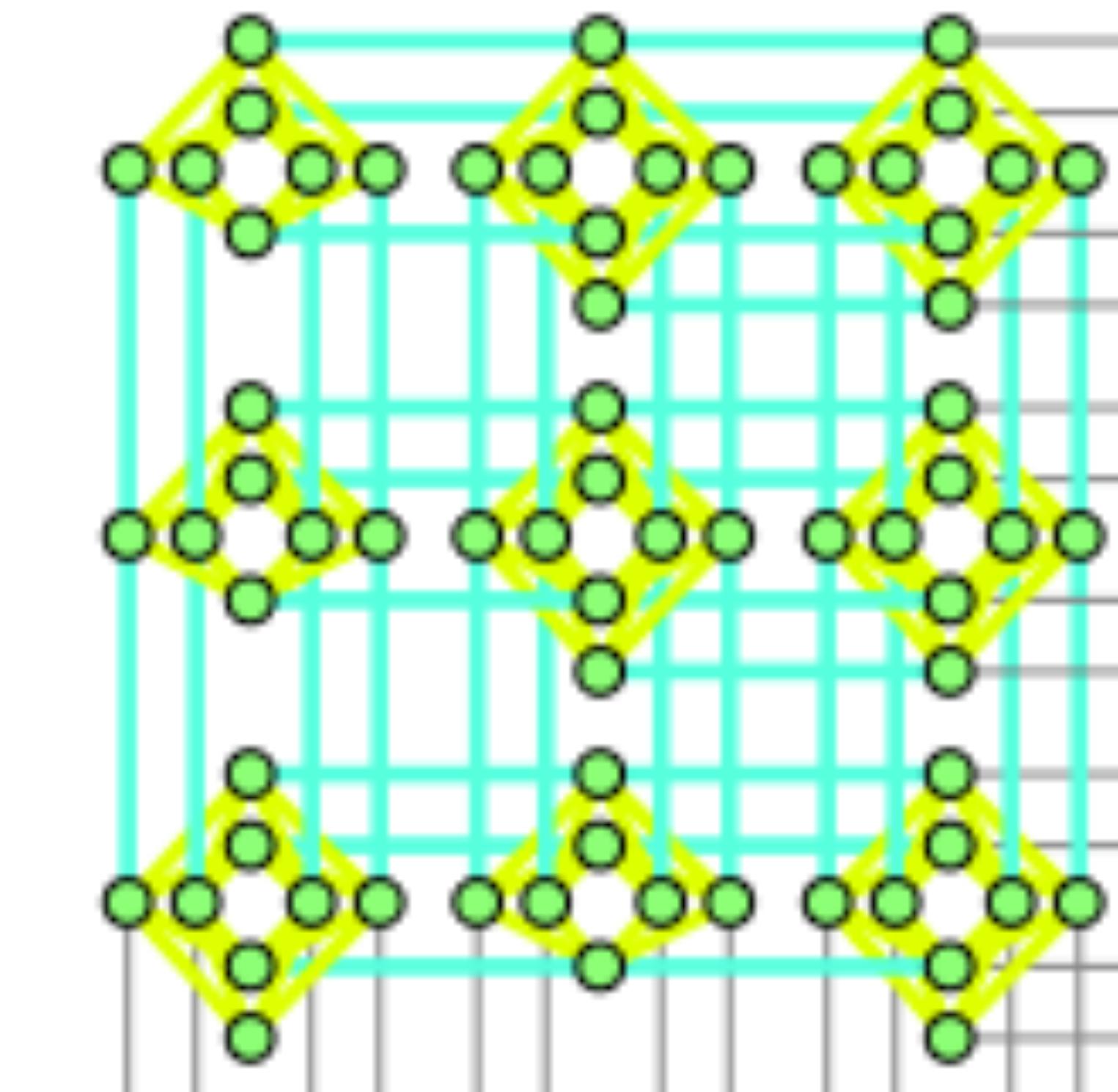
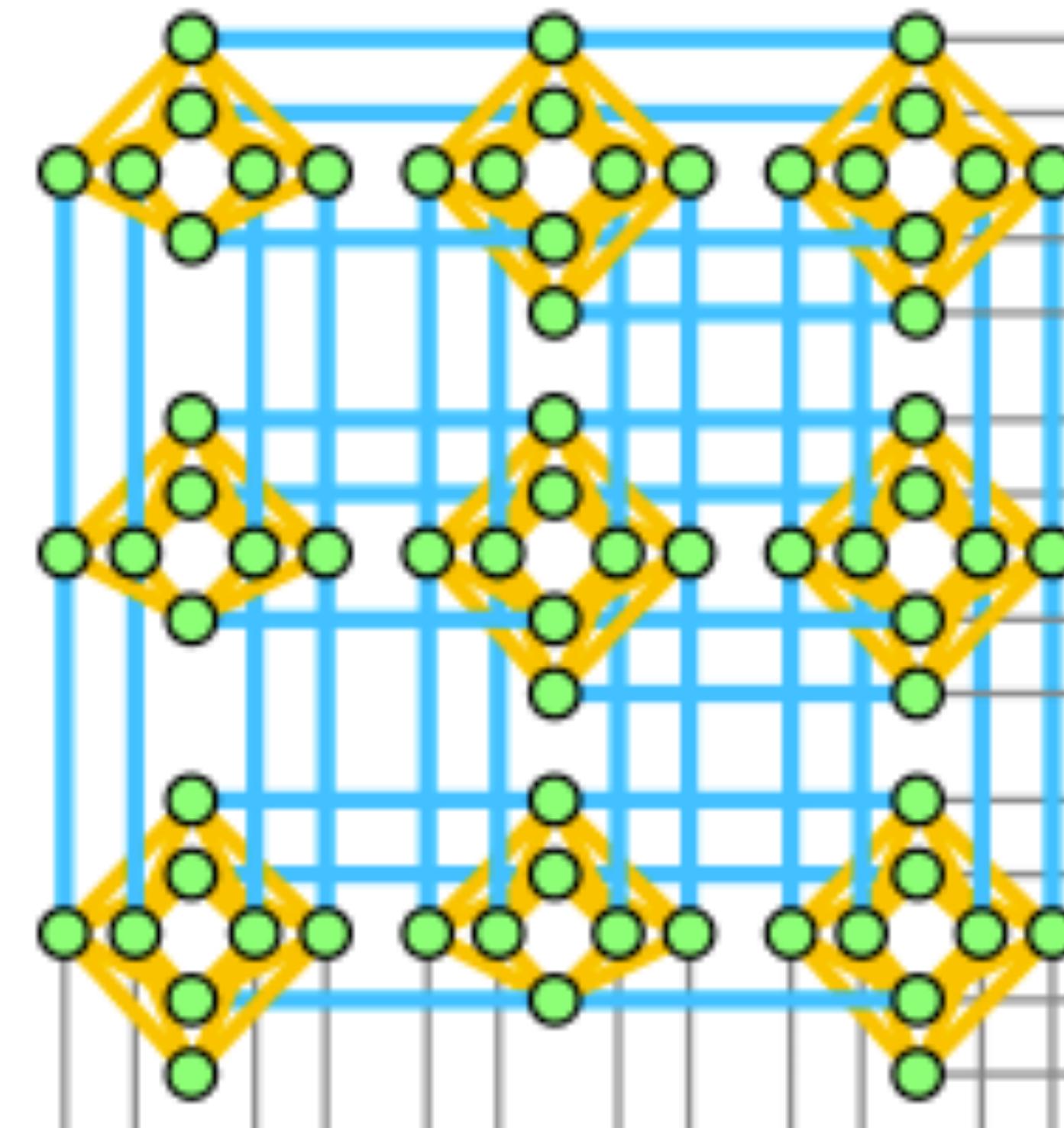
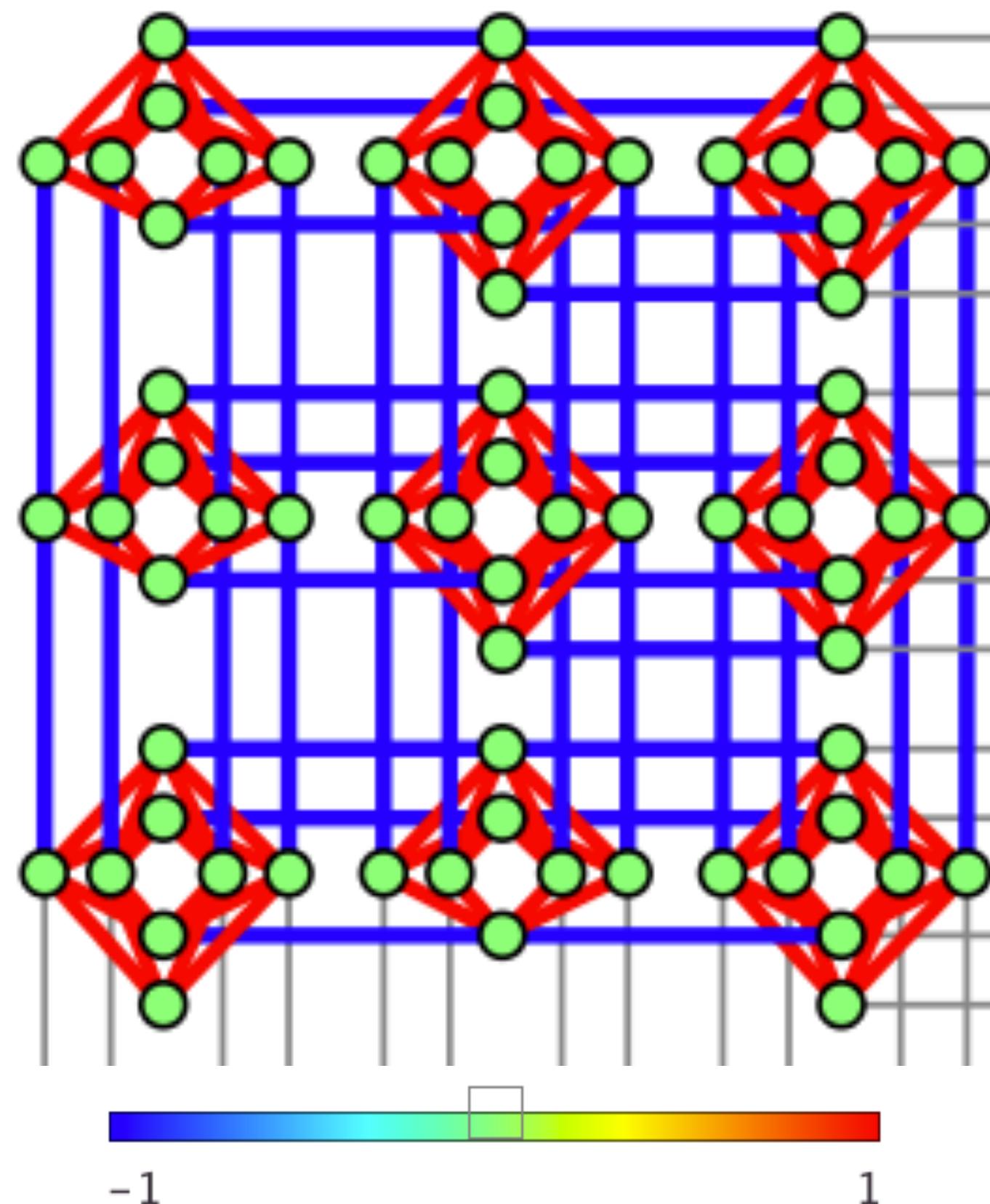
Boltzmanny Illustration



Boltzmanny Illustration

Weaken Couplings

simulates Boltzmann temp. increase



Boltzmanny Illustration

Submit Problem Configuration

Configurations

Parameters

Problem Parameters

Answer Mode

Histogram

Number of Reads

1000

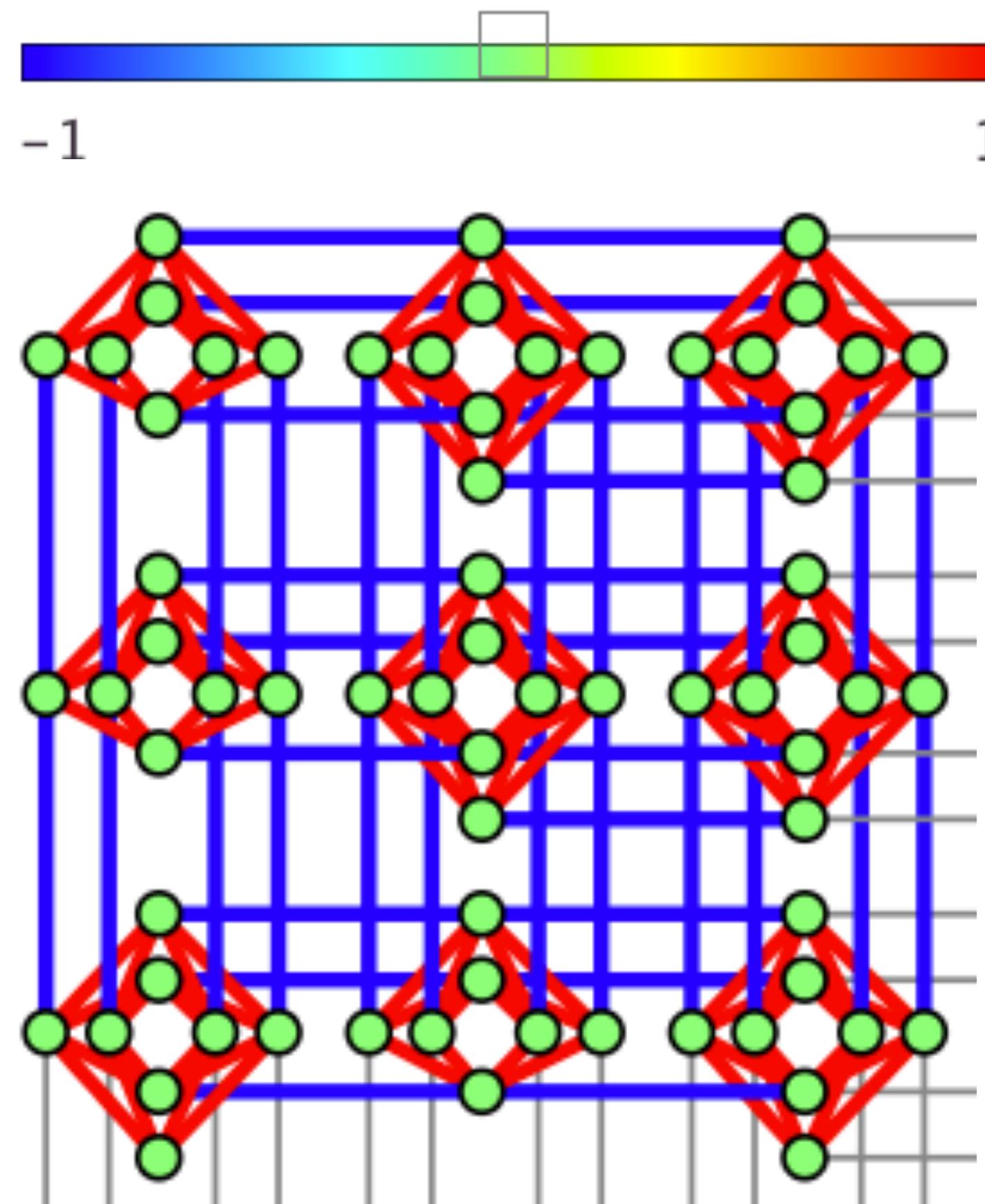
Number of reads.

Maximum Number of Answers

Maximum number of answers returned.

- Automatic Scaling**
- Automatically scale h and J values in Ising Hamiltonian to use their respective full ranges. If checked, h and J values will not be restricted to their respective ranges.

Boltzmanny Illustration - Step 1



Coupler Scale: 1.0

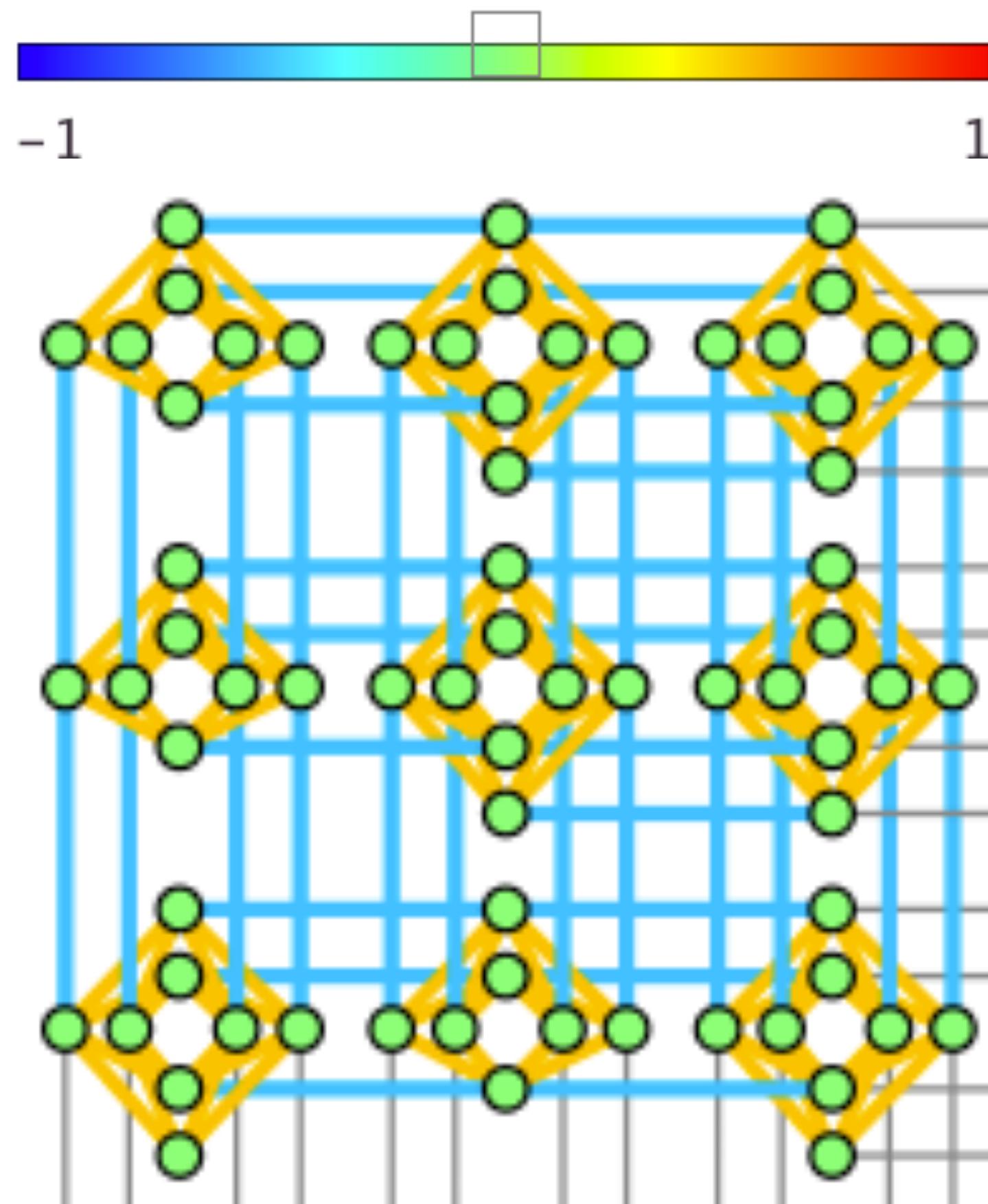
1000 Samples @ 20ms
792 @ -176
208 @ -176

Would be 50/50
if true Boltzmann

Boltzmanny Illustration - Step 1

1152 176	12 20 -1	96 102 1	112 116 1	193 198 1	209 212 1
0 4 1	16 20 1	97 102 1	113 116 1	194 198 1	210 212 1
1 4 1	17 20 1	98 102 1	114 116 1	195 198 1	211 212 1
2 4 1	18 20 1	99 102 1	115 116 1	192 199 1	205 213 -1
3 4 1	19 20 1	8 104 -1	109 117 -1	193 199 1	208 213 1
0 5 1	13 21 -1	9 105 -1	112 117 1	194 199 1	209 213 1
1 5 1	16 21 1	10 106 -1	113 117 1	195 199 1	210 213 1
2 5 1	17 21 1	11 107 -1	114 117 1	104 200 -1	211 213 1
3 5 1	18 21 1	100 108 -1	115 117 1	105 201 -1	206 214 -1
0 6 1	19 21 1	104 108 1	110 118 -1	106 202 -1	208 214 1
1 6 1	14 22 -1	105 108 1	112 118 1	107 203 -1	209 214 1
2 6 1	16 22 1	106 108 1	113 118 1	196 204 -1	210 214 1
3 6 1	17 22 1	107 108 1	114 118 1	200 204 1	211 214 1
4 12 -1	18 22 1	101 109 -1	115 118 1	201 204 1	208 215 1
8 12 1	19 22 1	104 109 1	111 119 -1	202 204 1	209 215 1
9 12 1	15 23 -1	105 109 1	112 119 1	203 204 1	210 215 1
10 12 1	16 23 1	106 109 1	113 119 1	197 205 -1	211 215 1
11 12 1	17 23 1	107 109 1	114 119 1	200 205 1	
5 13 -1	18 23 1	102 110 -1	115 119 1	201 205 1	
8 13 1	19 23 1	104 110 1	96 192 -1	202 205 1	
9 13 1	0 96 -1	105 110 1	97 193 -1	203 205 1	
10 13 1	1 97 -1	106 110 1	98 194 -1	198 206 -1	
11 13 1	2 98 -1	107 110 1	99 195 -1	200 206 1	
6 14 -1	3 99 -1	104 111 1	192 196 1	201 206 1	
8 14 1	96 100 1	105 111 1	193 196 1	202 206 1	
9 14 1	97 100 1	106 111 1	194 196 1	203 206 1	
10 14 1	98 100 1	107 111 1	195 196 1	112 208 -1	
11 14 1	99 100 1	16 112 -1	192 197 1	113 209 -1	
8 15 1	96 101 1	17 113 -1	193 197 1	114 210 -1	
9 15 1	97 101 1	18 114 -1	194 197 1	115 211 -1	
10 15 1	98 101 1	19 115 -1	195 197 1	204 212 -1	
11 15 1	99 101 1	108 116 -1	192 198 1	208 212 1	

Boltzmanny Illustration - Step 2



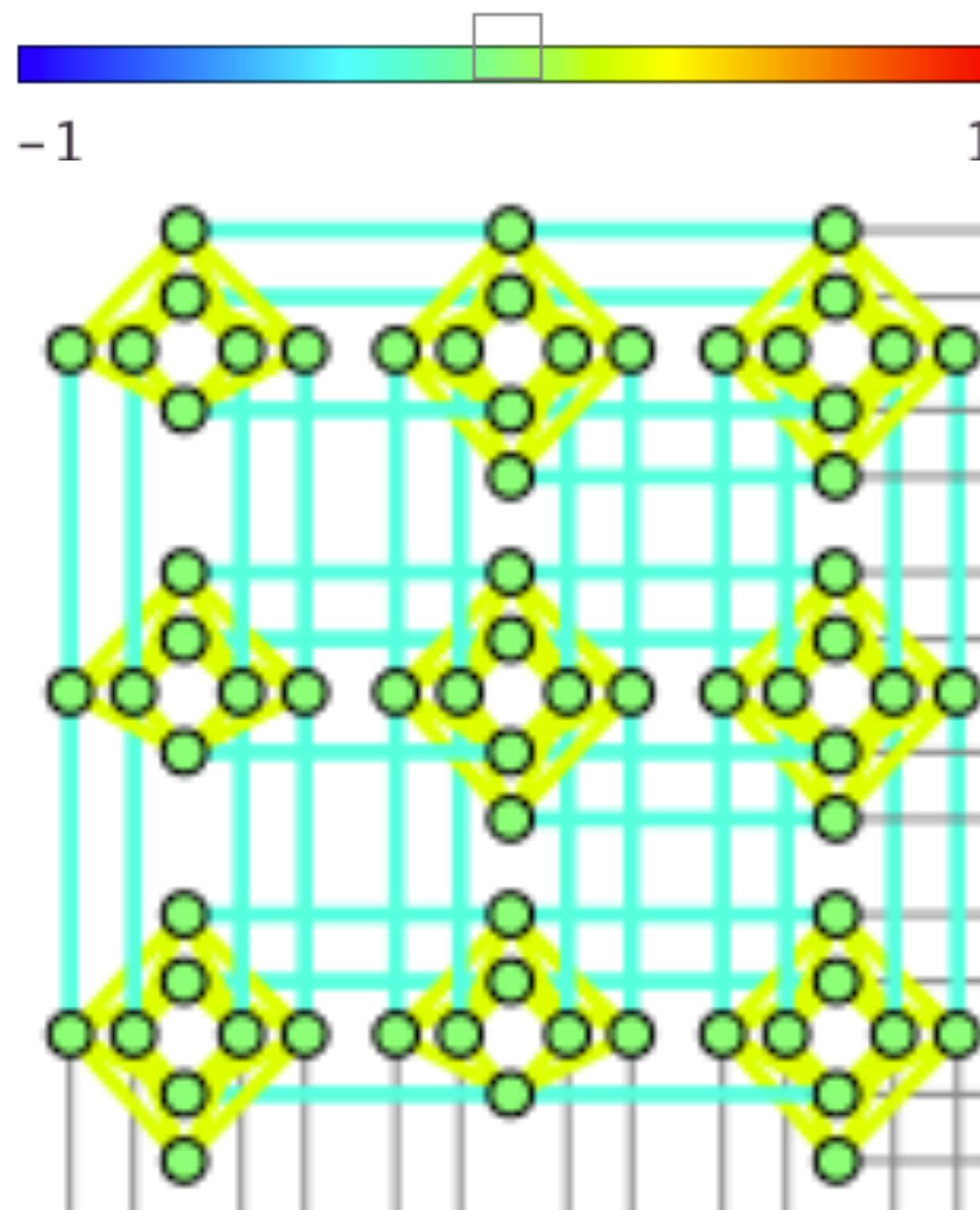
1000 Samples @ 20ms
727 @ -88
273 @ -88

Coupler Scale: 0.5 ← “increase temp.”

Boltzmanny Illustration - Step 2

1152 176	12 20 -0.5	96 102 0.5	112 116 0.5	193 198 0.5	209 212 0.5
0 4 0.5	16 20 0.5	97 102 0.5	113 116 0.5	194 198 0.5	210 212 0.5
1 4 0.5	17 20 0.5	98 102 0.5	114 116 0.5	195 198 0.5	211 212 0.5
2 4 0.5	18 20 0.5	99 102 0.5	115 116 0.5	192 199 0.5	205 213 -0.5
3 4 0.5	19 20 0.5	8 104 -0.5	109 117 -0.5	193 199 0.5	208 213 0.5
0 5 0.5	13 21 -0.5	9 105 -0.5	112 117 0.5	194 199 0.5	209 213 0.5
1 5 0.5	16 21 0.5	10 106 -0.5	113 117 0.5	195 199 0.5	210 213 0.5
2 5 0.5	17 21 0.5	11 107 -0.5	114 117 0.5	104 200 -0.5	211 213 0.5
3 5 0.5	18 21 0.5	100 108 -0.5	115 117 0.5	105 201 -0.5	206 214 -0.5
0 6 0.5	19 21 0.5	104 108 0.5	110 118 -0.5	106 202 -0.5	208 214 0.5
1 6 0.5	14 22 -0.5	105 108 0.5	112 118 0.5	107 203 -0.5	209 214 0.5
2 6 0.5	16 22 0.5	106 108 0.5	113 118 0.5	196 204 -0.5	210 214 0.5
3 6 0.5	17 22 0.5	107 108 0.5	114 118 0.5	200 204 0.5	211 214 0.5
4 12 -0.5	18 22 0.5	101 109 -0.5	115 118 0.5	201 204 0.5	208 215 0.5
8 12 0.5	19 22 0.5	104 109 0.5	111 119 -0.5	202 204 0.5	209 215 0.5
9 12 0.5	15 23 -0.5	105 109 0.5	112 119 0.5	203 204 0.5	210 215 0.5
10 12 0.5	16 23 0.5	106 109 0.5	113 119 0.5	197 205 -0.5	211 215 0.5
11 12 0.5	17 23 0.5	107 109 0.5	114 119 0.5	200 205 0.5	
5 13 -0.5	18 23 0.5	102 110 -0.5	115 119 0.5	201 205 0.5	
8 13 0.5	19 23 0.5	104 110 0.5	96 192 -0.5	202 205 0.5	
9 13 0.5	0 96 -0.5	105 110 0.5	97 193 -0.5	203 205 0.5	
10 13 0.5	1 97 -0.5	106 110 0.5	98 194 -0.5	198 206 -0.5	
11 13 0.5	2 98 -0.5	107 110 0.5	99 195 -0.5	200 206 0.5	
6 14 -0.5	3 99 -0.5	104 111 0.5	192 196 0.5	201 206 0.5	
8 14 0.5	96 100 0.5	105 111 0.5	193 196 0.5	202 206 0.5	
9 14 0.5	97 100 0.5	106 111 0.5	194 196 0.5	203 206 0.5	
10 14 0.5	98 100 0.5	107 111 0.5	195 196 0.5	112 208 -0.5	
11 14 0.5	99 100 0.5	16 112 -0.5	192 197 0.5	113 209 -0.5	
8 15 0.5	96 101 0.5	17 113 -0.5	193 197 0.5	114 210 -0.5	
9 15 0.5	97 101 0.5	18 114 -0.5	194 197 0.5	115 211 -0.5	
10 15 0.5	98 101 0.5	19 115 -0.5	195 197 0.5	204 212 -0.5	
11 15 0.5	99 101 0.5	108 116 -0.5	192 198 0.5	208 212 0.5	

Boltzmanny Illustration - Step 3



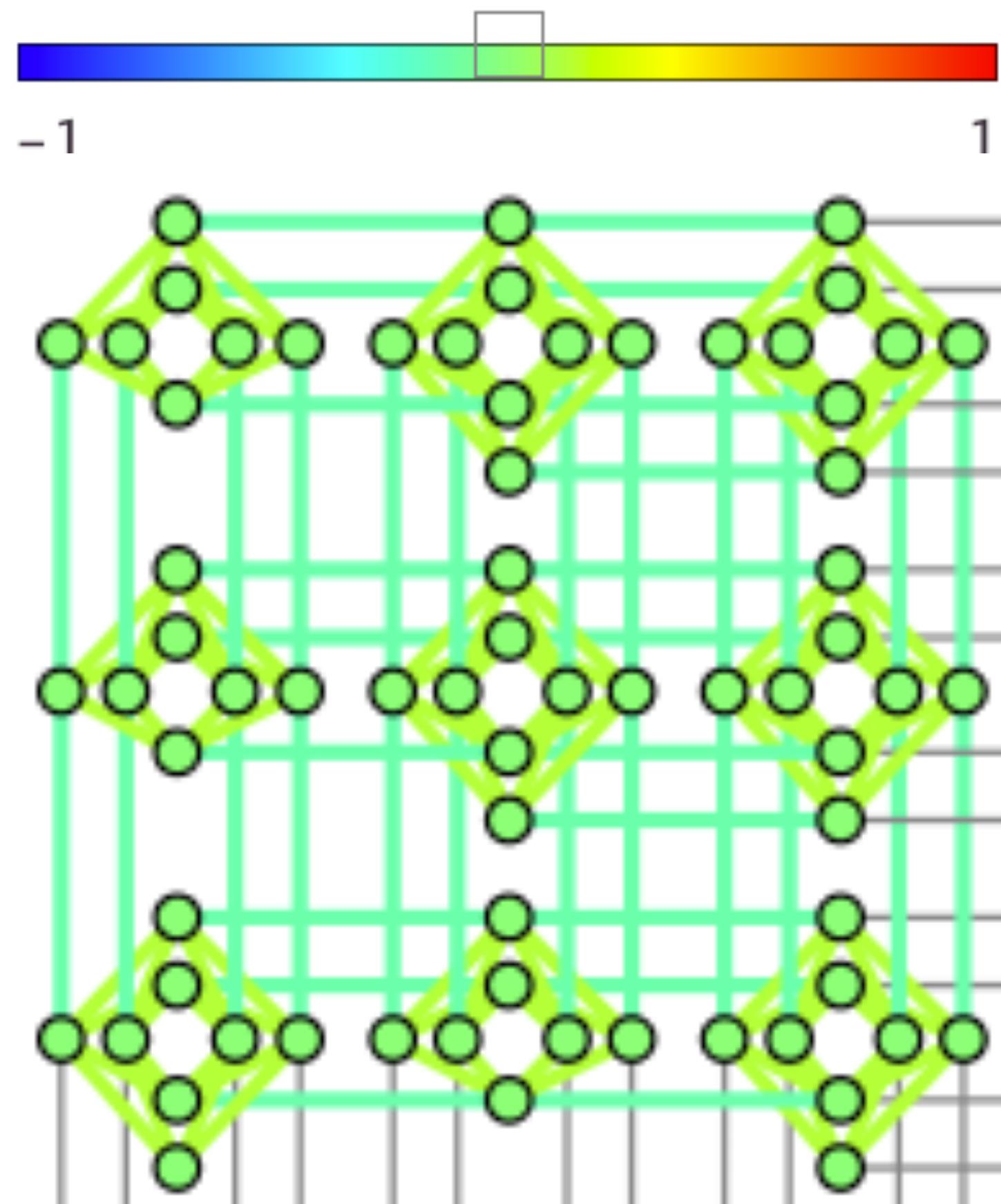
Coupler Scale: 0.25

1000 Samples @ 20ms
669 @ -44
331 @ -44

Boltzmanny Illustration - Step 3

1152 176	12 20 -0.25	96 102 0.25	112 116 0.25	193 198 0.25	209 212 0.25
0 4 0.25	16 20 0.25	97 102 0.25	113 116 0.25	194 198 0.25	210 212 0.25
1 4 0.25	17 20 0.25	98 102 0.25	114 116 0.25	195 198 0.25	211 212 0.25
2 4 0.25	18 20 0.25	99 102 0.25	115 116 0.25	192 199 0.25	205 213 -0.25
3 4 0.25	19 20 0.25	8 104 -0.25	109 117 -0.25	193 199 0.25	208 213 0.25
0 5 0.25	13 21 -0.25	9 105 -0.25	112 117 0.25	194 199 0.25	209 213 0.25
1 5 0.25	16 21 0.25	10 106 -0.25	113 117 0.25	195 199 0.25	210 213 0.25
2 5 0.25	17 21 0.25	11 107 -0.25	114 117 0.25	104 200 -0.25	211 213 0.25
3 5 0.25	18 21 0.25	100 108 -0.25	115 117 0.25	105 201 -0.25	206 214 -0.25
0 6 0.25	19 21 0.25	104 108 0.25	110 118 -0.25	106 202 -0.25	208 214 0.25
1 6 0.25	14 22 -0.25	105 108 0.25	112 118 0.25	107 203 -0.25	209 214 0.25
2 6 0.25	16 22 0.25	106 108 0.25	113 118 0.25	196 204 -0.25	210 214 0.25
3 6 0.25	17 22 0.25	107 108 0.25	114 118 0.25	200 204 0.25	211 214 0.25
4 12 -0.25	18 22 0.25	101 109 -0.25	115 118 0.25	201 204 0.25	208 215 0.25
8 12 0.25	19 22 0.25	104 109 0.25	111 119 -0.25	202 204 0.25	209 215 0.25
9 12 0.25	15 23 -0.25	105 109 0.25	112 119 0.25	203 204 0.25	210 215 0.25
10 12 0.25	16 23 0.25	106 109 0.25	113 119 0.25	197 205 -0.25	211 215 0.25
11 12 0.25	17 23 0.25	107 109 0.25	114 119 0.25	200 205 0.25	
5 13 -0.25	18 23 0.25	102 110 -0.25	115 119 0.25	201 205 0.25	
8 13 0.25	19 23 0.25	104 110 0.25	96 192 -0.25	202 205 0.25	
9 13 0.25	0 96 -0.25	105 110 0.25	97 193 -0.25	203 205 0.25	
10 13 0.25	1 97 -0.25	106 110 0.25	98 194 -0.25	198 206 -0.25	
11 13 0.25	2 98 -0.25	107 110 0.25	99 195 -0.25	200 206 0.25	
6 14 -0.25	3 99 -0.25	104 111 0.25	192 196 0.25	201 206 0.25	
8 14 0.25	96 100 0.25	105 111 0.25	193 196 0.25	202 206 0.25	
9 14 0.25	97 100 0.25	106 111 0.25	194 196 0.25	203 206 0.25	
10 14 0.25	98 100 0.25	107 111 0.25	195 196 0.25	112 208 -0.25	
11 14 0.25	99 100 0.25	16 112 -0.25	192 197 0.25	113 209 -0.25	
8 15 0.25	96 101 0.25	17 113 -0.25	193 197 0.25	114 210 -0.25	
9 15 0.25	97 101 0.25	18 114 -0.25	194 197 0.25	115 211 -0.25	
10 15 0.25	98 101 0.25	19 115 -0.25	195 197 0.25	204 212 -0.25	
11 15 0.25	99 101 0.25	108 116 -0.25	192 198 0.25	208 212 0.25	

Boltzmanny Illustration - Step 4



Coupler Scale: 0.125

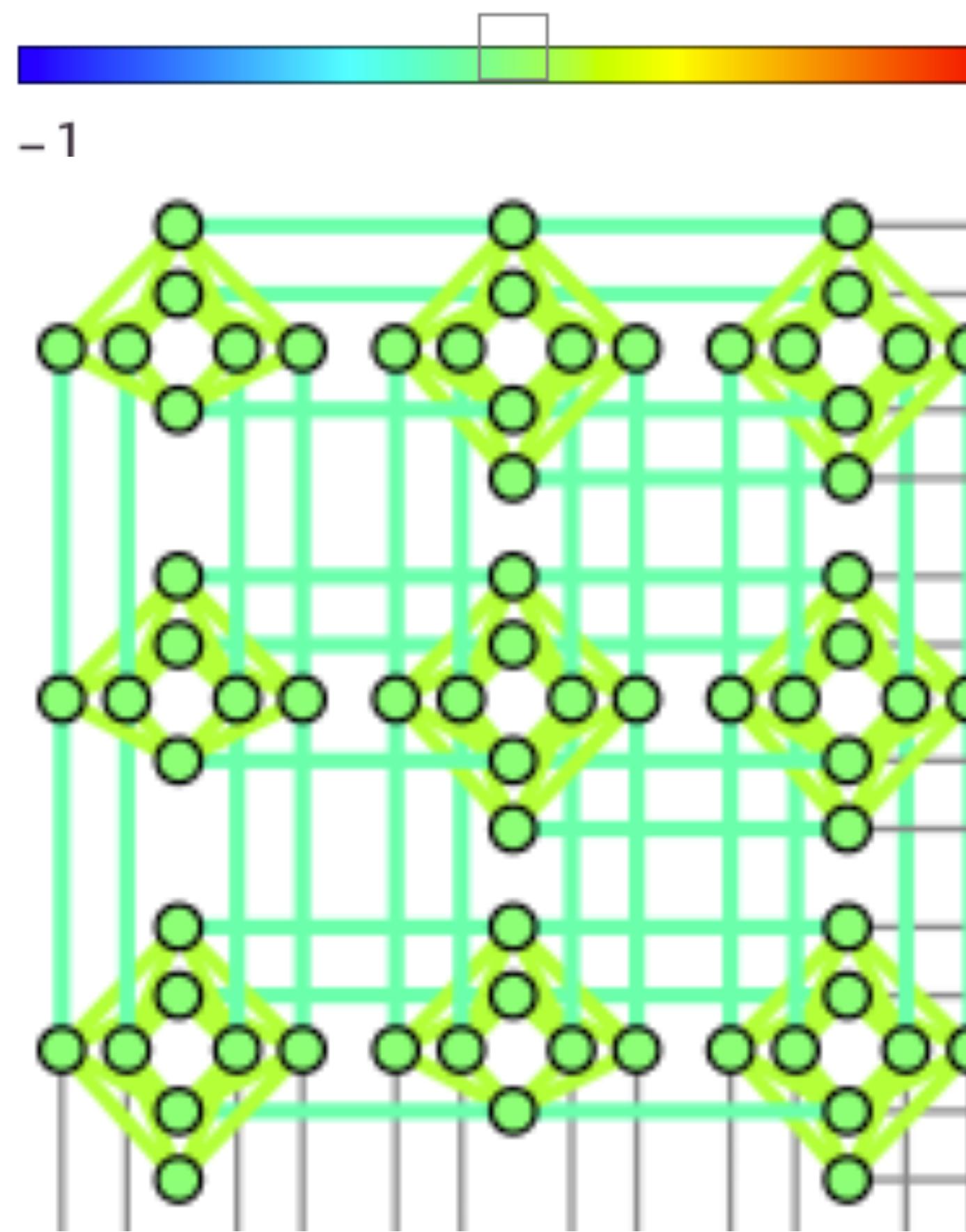
1000 Samples @ 20ms
556 @ -22
430 @ -22
14 @ other

High temp. bumping
out of ground state

Boltzmanny Illustration - Step 4

1152 176	12 20 -0.125	96 102 0.125	112 116 0.125	193 198 0.125	209 212 0.125
0 4 0.125	16 20 0.125	97 102 0.125	113 116 0.125	194 198 0.125	210 212 0.125
1 4 0.125	17 20 0.125	98 102 0.125	114 116 0.125	195 198 0.125	211 212 0.125
2 4 0.125	18 20 0.125	99 102 0.125	115 116 0.125	192 199 0.125	205 213 -0.125
3 4 0.125	19 20 0.125	8 104 -0.125	109 117 -0.125	193 199 0.125	208 213 0.125
0 5 0.125	13 21 -0.125	9 105 -0.125	112 117 0.125	194 199 0.125	209 213 0.125
1 5 0.125	16 21 0.125	10 106 -0.125	113 117 0.125	195 199 0.125	210 213 0.125
2 5 0.125	17 21 0.125	11 107 -0.125	114 117 0.125	104 200 -0.125	211 213 0.125
3 5 0.125	18 21 0.125	100 108 -0.125	115 117 0.125	105 201 -0.125	206 214 -0.125
0 6 0.125	19 21 0.125	104 108 0.125	110 118 -0.125	106 202 -0.125	208 214 0.125
1 6 0.125	14 22 -0.125	105 108 0.125	112 118 0.125	107 203 -0.125	209 214 0.125
2 6 0.125	16 22 0.125	106 108 0.125	113 118 0.125	196 204 -0.125	210 214 0.125
3 6 0.125	17 22 0.125	107 108 0.125	114 118 0.125	200 204 0.125	211 214 0.125
4 12 -0.125	18 22 0.125	101 109 -0.125	115 118 0.125	201 204 0.125	208 215 0.125
8 12 0.125	19 22 0.125	104 109 0.125	111 119 -0.125	202 204 0.125	209 215 0.125
9 12 0.125	15 23 -0.125	105 109 0.125	112 119 0.125	203 204 0.125	210 215 0.125
10 12 0.125	16 23 0.125	106 109 0.125	113 119 0.125	197 205 -0.125	211 215 0.125
11 12 0.125	17 23 0.125	107 109 0.125	114 119 0.125	200 205 0.125	
5 13 -0.125	18 23 0.125	102 110 -0.125	115 119 0.125	201 205 0.125	
8 13 0.125	19 23 0.125	104 110 0.125	96 192 -0.125	202 205 0.125	
9 13 0.125	0 96 -0.125	105 110 0.125	97 193 -0.125	203 205 0.125	
10 13 0.125	1 97 -0.125	106 110 0.125	98 194 -0.125	198 206 -0.125	
11 13 0.125	2 98 -0.125	107 110 0.125	99 195 -0.125	200 206 0.125	
6 14 -0.125	3 99 -0.125	104 111 0.125	192 196 0.125	201 206 0.125	
8 14 0.125	96 100 0.125	105 111 0.125	193 196 0.125	202 206 0.125	
9 14 0.125	97 100 0.125	106 111 0.125	194 196 0.125	203 206 0.125	
10 14 0.125	98 100 0.125	107 111 0.125	195 196 0.125	112 208 -0.125	
11 14 0.125	99 100 0.125	16 112 -0.125	192 197 0.125	113 209 -0.125	
8 15 0.125	96 101 0.125	17 113 -0.125	193 197 0.125	114 210 -0.125	
9 15 0.125	97 101 0.125	18 114 -0.125	194 197 0.125	115 211 -0.125	
10 15 0.125	98 101 0.125	19 115 -0.125	195 197 0.125	204 212 -0.125	
11 15 0.125	99 101 0.125	108 116 -0.125	192 198 0.125	208 212 0.125	

Boltzmanny Illustration - Step 5



Coupler Scale: 0.0625

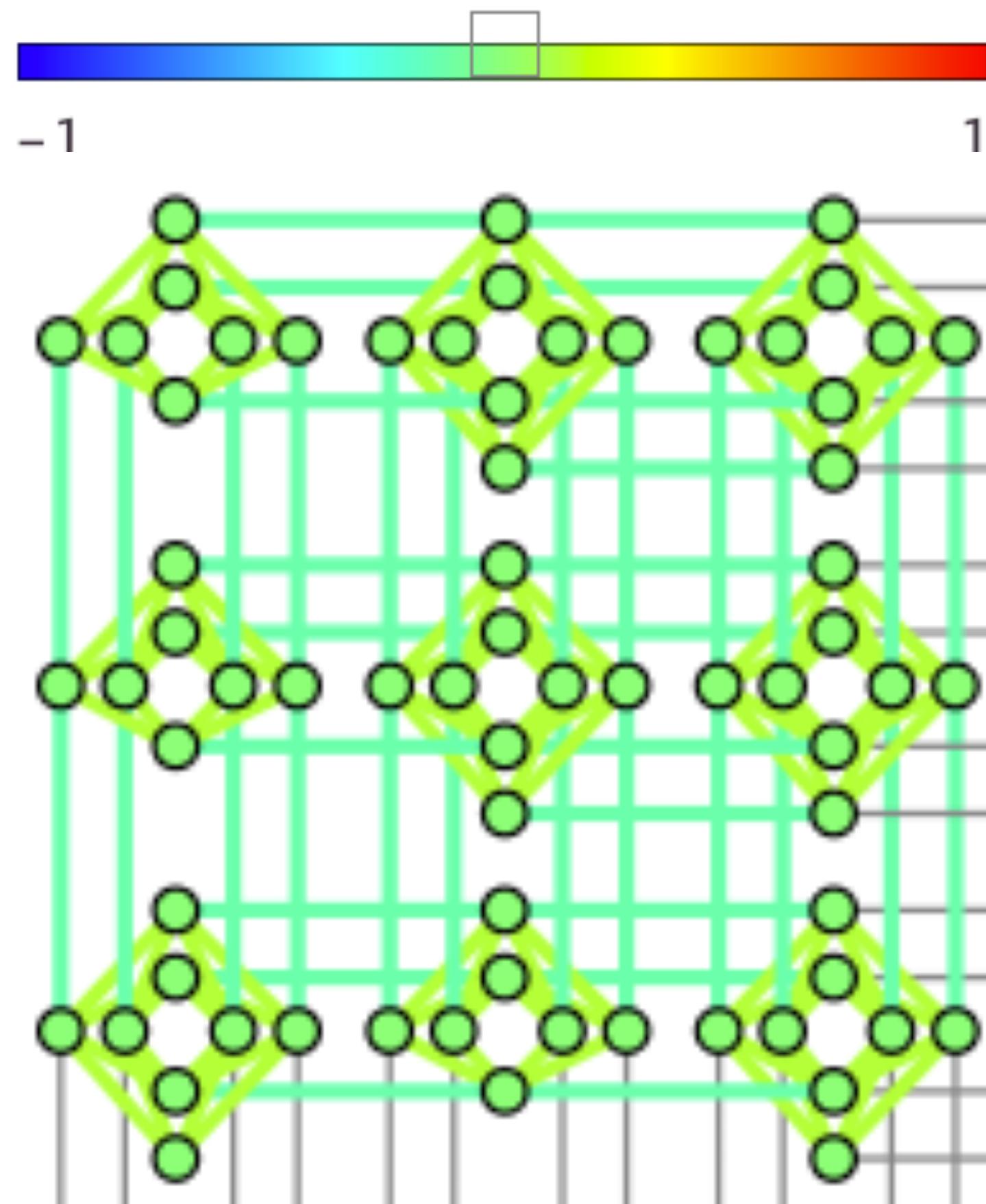
1000 Samples @ 20ms
458 @ -11
435 @ -11
107 @ other

Higher temp.
more bumping

Boltzmanny Illustration - Step 5

1152 176	12 20 -0.0625	96 102 0.0625	112 116 0.0625	193 198 0.0625	209 212 0.0625
0 4 0.0625	16 20 0.0625	97 102 0.0625	113 116 0.0625	194 198 0.0625	210 212 0.0625
1 4 0.0625	17 20 0.0625	98 102 0.0625	114 116 0.0625	195 198 0.0625	211 212 0.0625
2 4 0.0625	18 20 0.0625	99 102 0.0625	115 116 0.0625	192 199 0.0625	205 213 -0.0625
3 4 0.0625	19 20 0.0625	8 104 -0.0625	109 117 -0.0625	193 199 0.0625	208 213 0.0625
0 5 0.0625	13 21 -0.0625	9 105 -0.0625	112 117 0.0625	194 199 0.0625	209 213 0.0625
1 5 0.0625	16 21 0.0625	10 106 -0.0625	113 117 0.0625	195 199 0.0625	210 213 0.0625
2 5 0.0625	17 21 0.0625	11 107 -0.0625	114 117 0.0625	104 200 -0.0625	211 213 0.0625
3 5 0.0625	18 21 0.0625	100 108 -0.0625	115 117 0.0625	105 201 -0.0625	206 214 -0.0625
0 6 0.0625	19 21 0.0625	104 108 0.0625	110 118 -0.0625	106 202 -0.0625	208 214 0.0625
1 6 0.0625	14 22 -0.0625	105 108 0.0625	112 118 0.0625	107 203 -0.0625	209 214 0.0625
2 6 0.0625	16 22 0.0625	106 108 0.0625	113 118 0.0625	196 204 -0.0625	210 214 0.0625
3 6 0.0625	17 22 0.0625	107 108 0.0625	114 118 0.0625	200 204 0.0625	211 214 0.0625
4 12 -0.0625	18 22 0.0625	101 109 -0.0625	115 118 0.0625	201 204 0.0625	208 215 0.0625
8 12 0.0625	19 22 0.0625	104 109 0.0625	111 119 -0.0625	202 204 0.0625	209 215 0.0625
9 12 0.0625	15 23 -0.0625	105 109 0.0625	112 119 0.0625	203 204 0.0625	210 215 0.0625
10 12 0.0625	16 23 0.0625	106 109 0.0625	113 119 0.0625	197 205 -0.0625	211 215 0.0625
11 12 0.0625	17 23 0.0625	107 109 0.0625	114 119 0.0625	200 205 0.0625	
5 13 -0.0625	18 23 0.0625	102 110 -0.0625	115 119 0.0625	201 205 0.0625	
8 13 0.0625	19 23 0.0625	104 110 0.0625	96 192 -0.0625	202 205 0.0625	
9 13 0.0625	0 96 -0.0625	105 110 0.0625	97 193 -0.0625	203 205 0.0625	
10 13 0.0625	1 97 -0.0625	106 110 0.0625	98 194 -0.0625	198 206 -0.0625	
11 13 0.0625	2 98 -0.0625	107 110 0.0625	99 195 -0.0625	200 206 0.0625	
6 14 -0.0625	3 99 -0.0625	104 111 0.0625	192 196 0.0625	201 206 0.0625	
8 14 0.0625	96 100 0.0625	105 111 0.0625	193 196 0.0625	202 206 0.0625	
9 14 0.0625	97 100 0.0625	106 111 0.0625	194 196 0.0625	203 206 0.0625	
10 14 0.0625	98 100 0.0625	107 111 0.0625	195 196 0.0625	112 208 -0.0625	
11 14 0.0625	99 100 0.0625	16 112 -0.0625	192 197 0.0625	113 209 -0.0625	
8 15 0.0625	96 101 0.0625	17 113 -0.0625	193 197 0.0625	114 210 -0.0625	
9 15 0.0625	97 101 0.0625	18 114 -0.0625	194 197 0.0625	115 211 -0.0625	
10 15 0.0625	98 101 0.0625	19 115 -0.0625	195 197 0.0625	204 212 -0.0625	
11 15 0.0625	99 101 0.0625	108 116 -0.0625	192 198 0.0625	208 212 0.0625	

Boltzmanny Illustration - Step 6



Coupler Scale: 0.03125

1000 Samples @ 20ms
22 @ -5.5
24 @ -5.5
954 @ other

Almost Pure Randomness

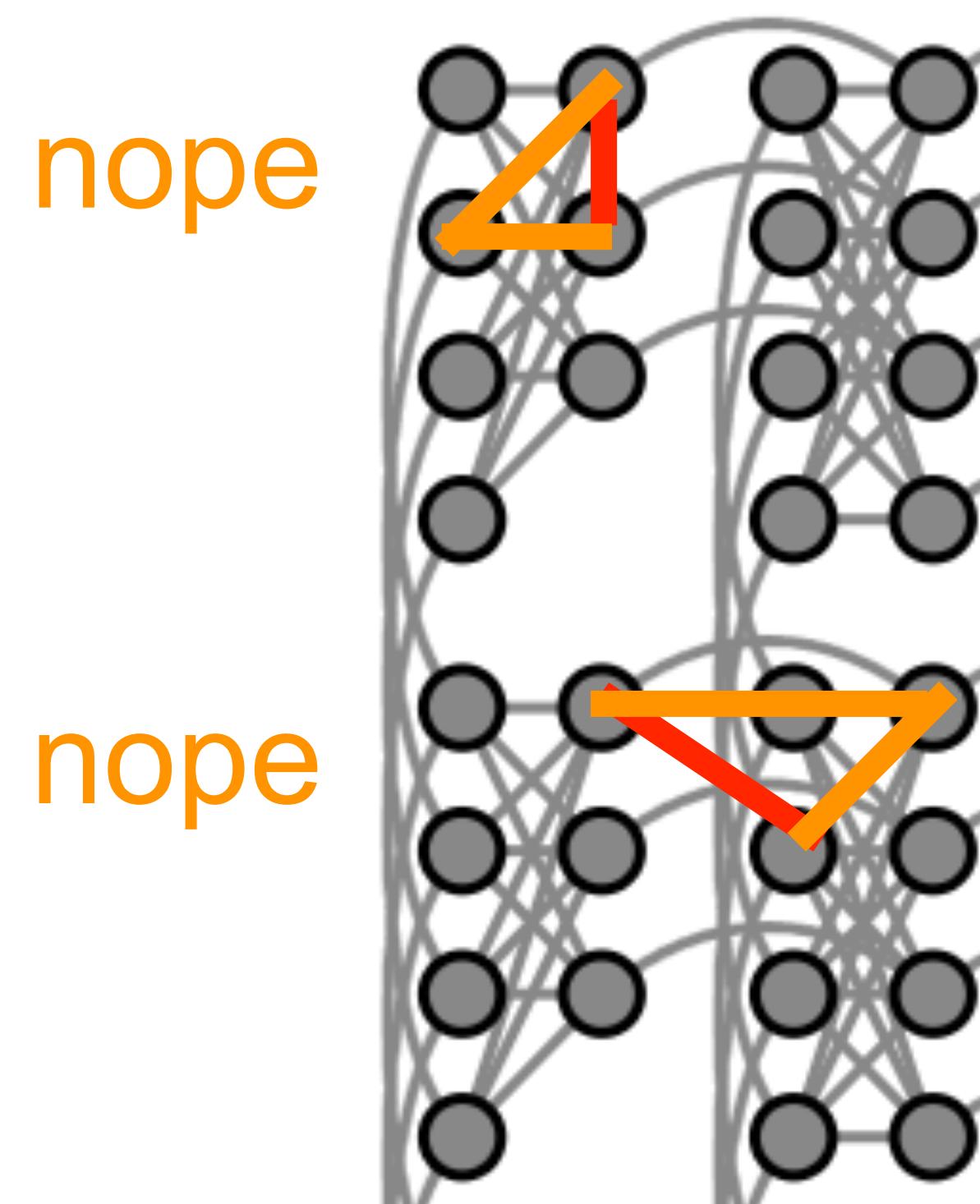
Boltzmanny Illustration - Step 6

1152 176	12 20 -0.03125	96 102 0.03125	112 116 0.03125	193 198 0.03125	209 212 0.03125
0 4 0.03125	16 20 0.03125	97 102 0.03125	113 116 0.03125	194 198 0.03125	210 212 0.03125
1 4 0.03125	17 20 0.03125	98 102 0.03125	114 116 0.03125	195 198 0.03125	211 212 0.03125
2 4 0.03125	18 20 0.03125	99 102 0.03125	115 116 0.03125	192 199 0.03125	205 213 -0.03125
3 4 0.03125	19 20 0.03125	8 104 -0.03125	109 117 -0.03125	193 199 0.03125	208 213 0.03125
0 5 0.03125	13 21 -0.03125	9 105 -0.03125	112 117 0.03125	194 199 0.03125	209 213 0.03125
1 5 0.03125	16 21 0.03125	10 106 -0.03125	113 117 0.03125	195 199 0.03125	210 213 0.03125
2 5 0.03125	17 21 0.03125	11 107 -0.03125	114 117 0.03125	104 200 -0.03125	211 213 0.03125
3 5 0.03125	18 21 0.03125	100 108 -0.03125	115 117 0.03125	105 201 -0.03125	206 214 -0.03125
0 6 0.03125	19 21 0.03125	104 108 0.03125	110 118 -0.03125	106 202 -0.03125	208 214 0.03125
1 6 0.03125	14 22 -0.03125	105 108 0.03125	112 118 0.03125	107 203 -0.03125	209 214 0.03125
2 6 0.03125	16 22 0.03125	106 108 0.03125	113 118 0.03125	196 204 -0.03125	210 214 0.03125
3 6 0.03125	17 22 0.03125	107 108 0.03125	114 118 0.03125	200 204 0.03125	211 214 0.03125
4 12 -0.03125	18 22 0.03125	101 109 -0.03125	115 118 0.03125	201 204 0.03125	208 215 0.03125
8 12 0.03125	19 22 0.03125	104 109 0.03125	111 119 -0.03125	202 204 0.03125	209 215 0.03125
9 12 0.03125	15 23 -0.03125	105 109 0.03125	112 119 0.03125	203 204 0.03125	210 215 0.03125
10 12 0.03125	16 23 0.03125	106 109 0.03125	113 119 0.03125	197 205 -0.03125	211 215 0.03125
11 12 0.03125	17 23 0.03125	107 109 0.03125	114 119 0.03125	200 205 0.03125	
5 13 -0.03125	18 23 0.03125	102 110 -0.03125	115 119 0.03125	201 205 0.03125	
8 13 0.03125	19 23 0.03125	104 110 0.03125	96 192 -0.03125	202 205 0.03125	
9 13 0.03125	0 96 -0.03125	105 110 0.03125	97 193 -0.03125	203 205 0.03125	
10 13 0.03125	1 97 -0.03125	106 110 0.03125	98 194 -0.03125	198 206 -0.03125	
11 13 0.03125	2 98 -0.03125	107 110 0.03125	99 195 -0.03125	200 206 0.03125	
6 14 -0.03125	3 99 -0.03125	104 111 0.03125	192 196 0.03125	201 206 0.03125	
8 14 0.03125	96 100 0.03125	105 111 0.03125	193 196 0.03125	202 206 0.03125	
9 14 0.03125	97 100 0.03125	106 111 0.03125	194 196 0.03125	203 206 0.03125	
10 14 0.03125	98 100 0.03125	107 111 0.03125	195 196 0.03125	112 208 -0.03125	
11 14 0.03125	99 100 0.03125	16 112 -0.03125	192 197 0.03125	113 209 -0.03125	
8 15 0.03125	96 101 0.03125	17 113 -0.03125	193 197 0.03125	114 210 -0.03125	
9 15 0.03125	97 101 0.03125	18 114 -0.03125	194 197 0.03125	115 211 -0.03125	
10 15 0.03125	98 101 0.03125	19 115 -0.03125	195 197 0.03125	204 212 -0.03125	
11 15 0.03125	99 101 0.03125	108 116 -0.03125	192 198 0.03125	208 212 0.03125	

Challenges with Chains

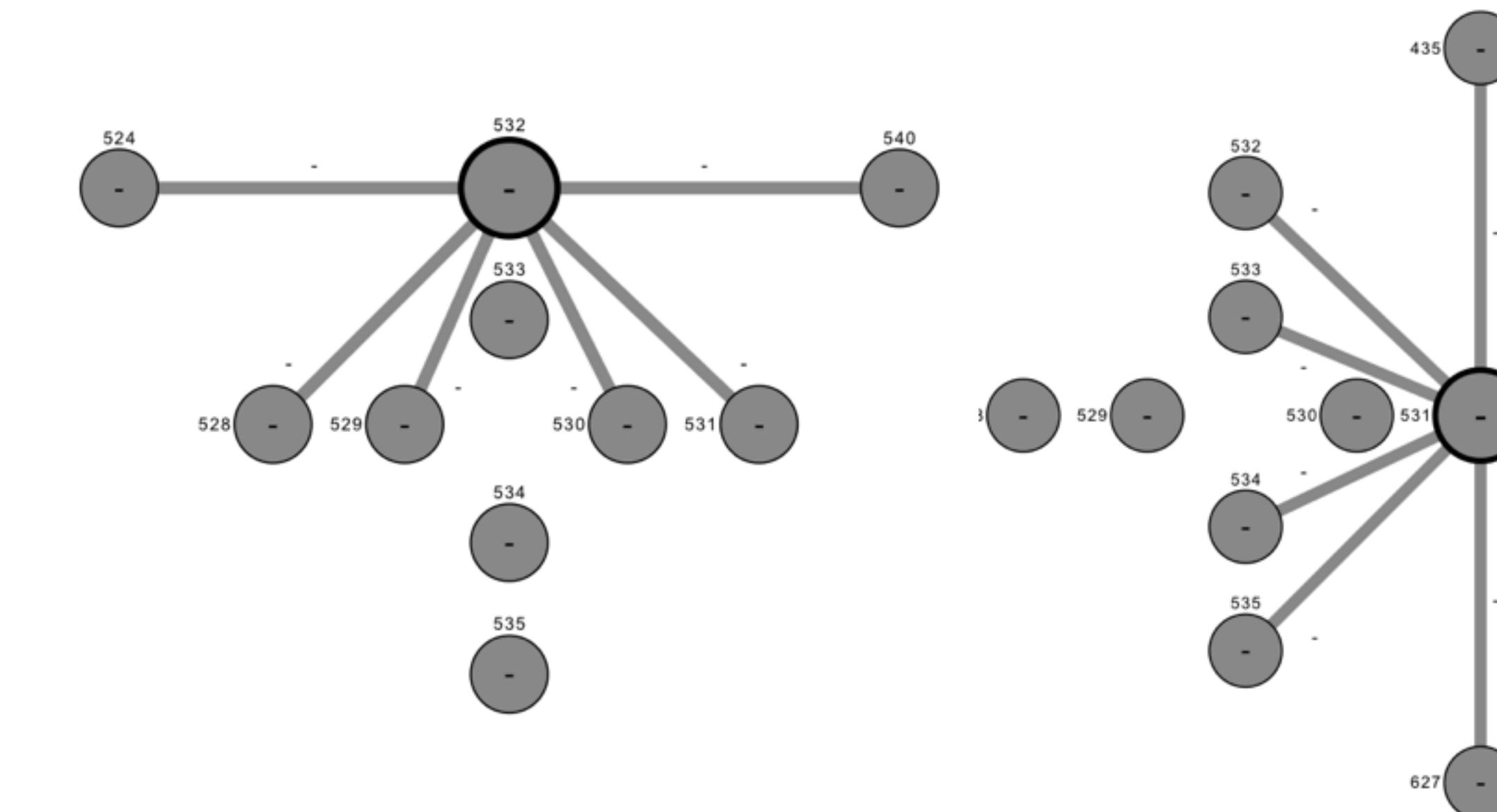
Properties of the Chimera Graph

Bipartide Graph



No Odd Length Cycles

Max Node Degree = 6

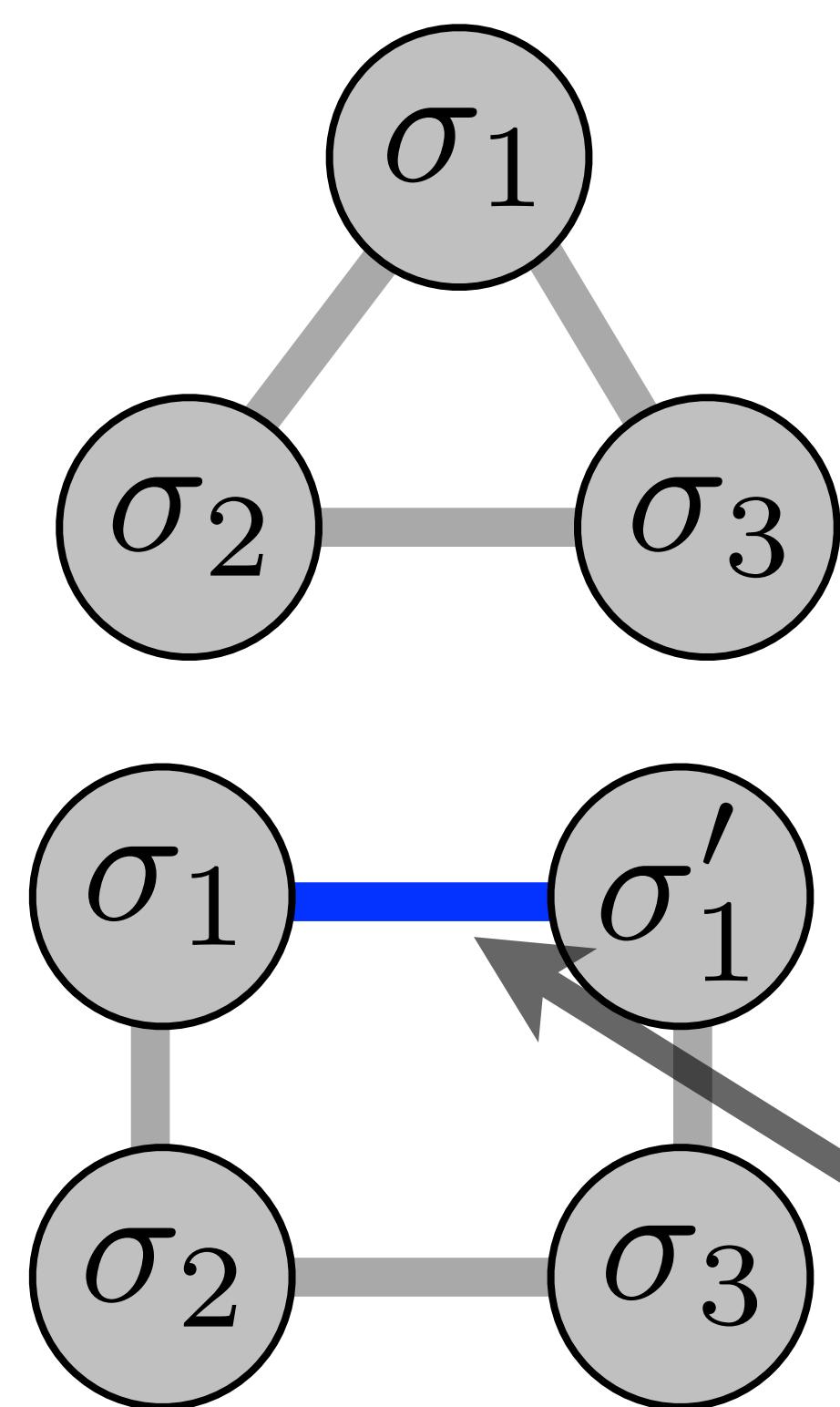


What are Chains?

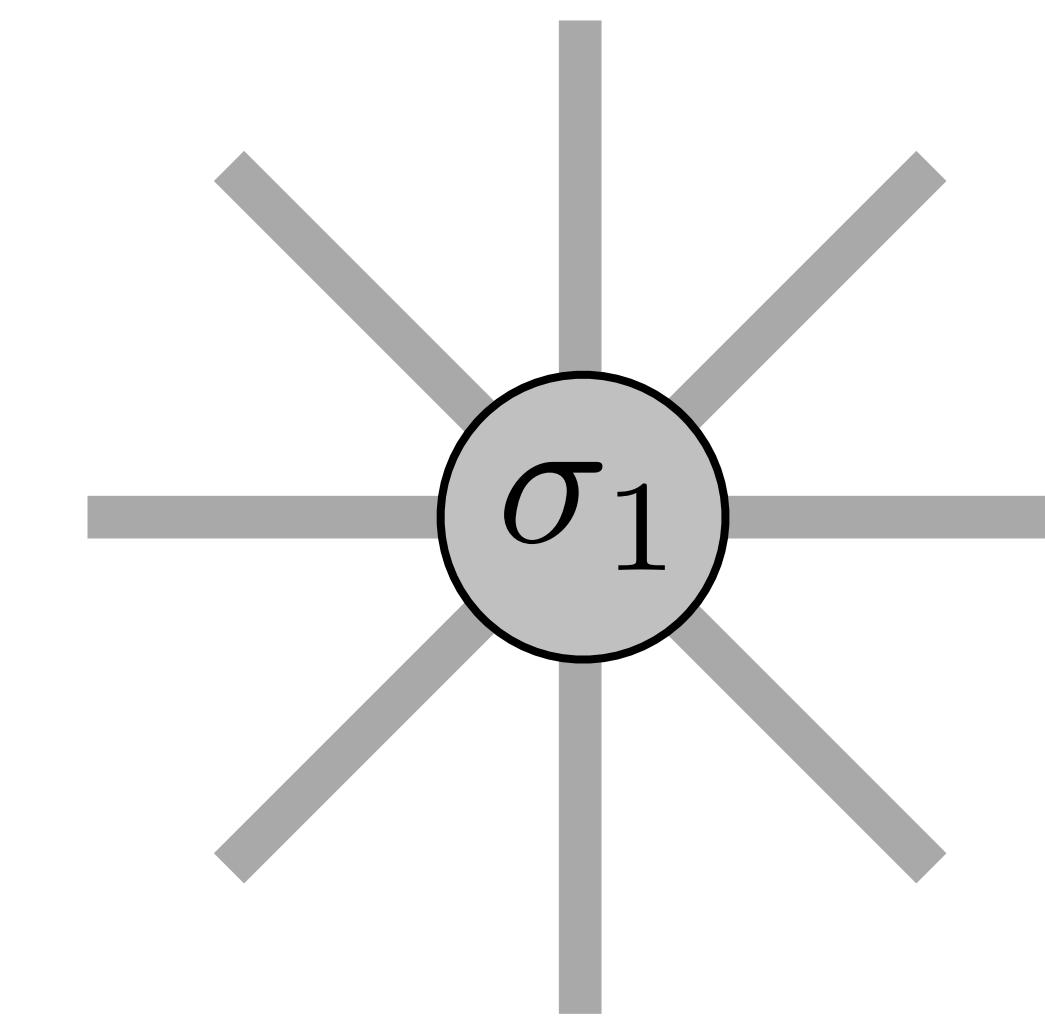
Logical Problem

Physical Implementation

Case 1

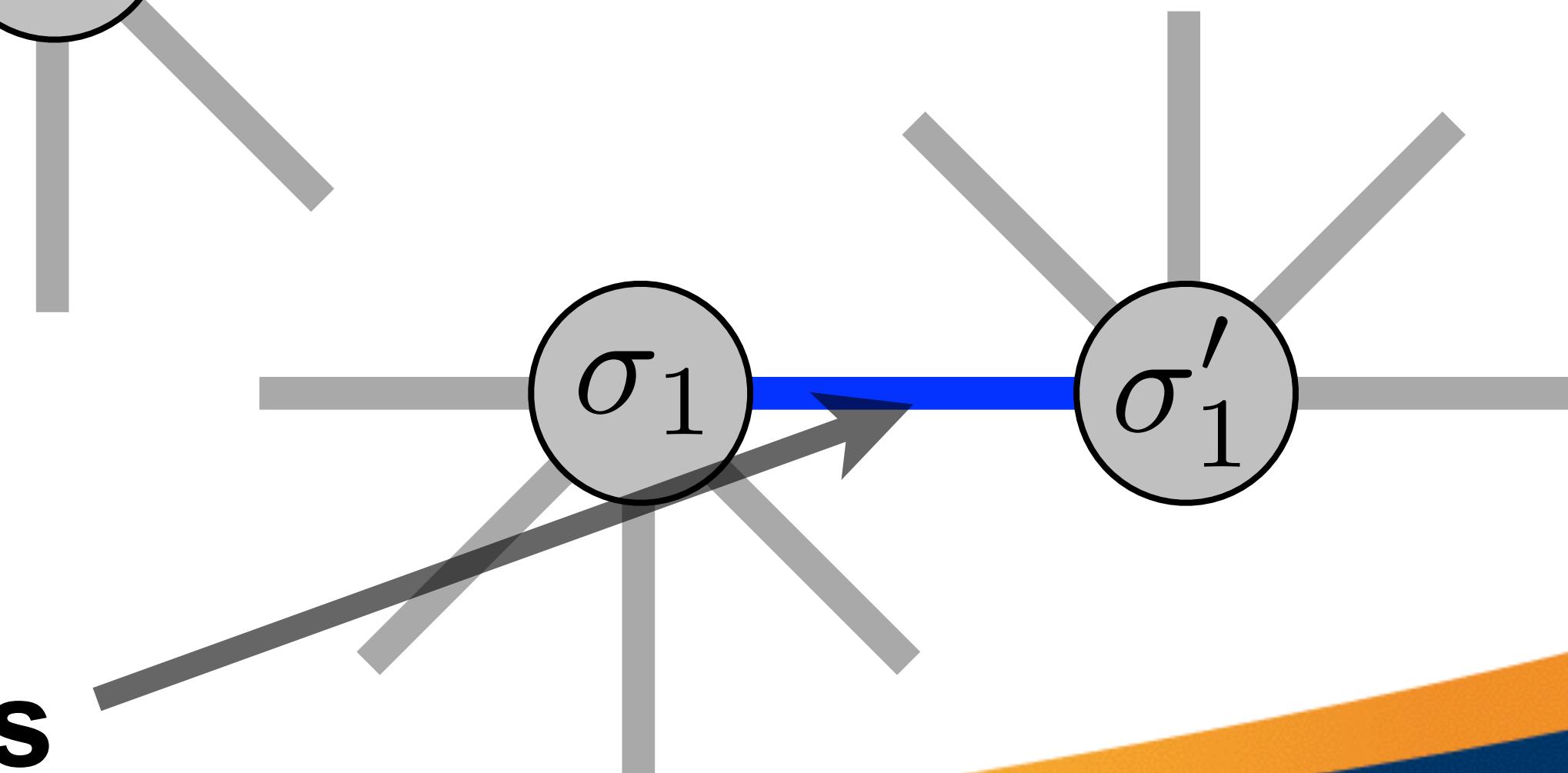
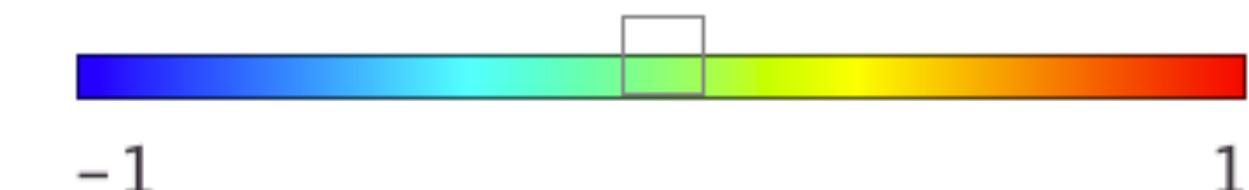


Case 2

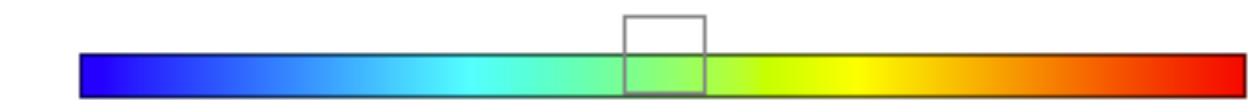


Chains

$$\sigma \in \{-1, 1\}$$

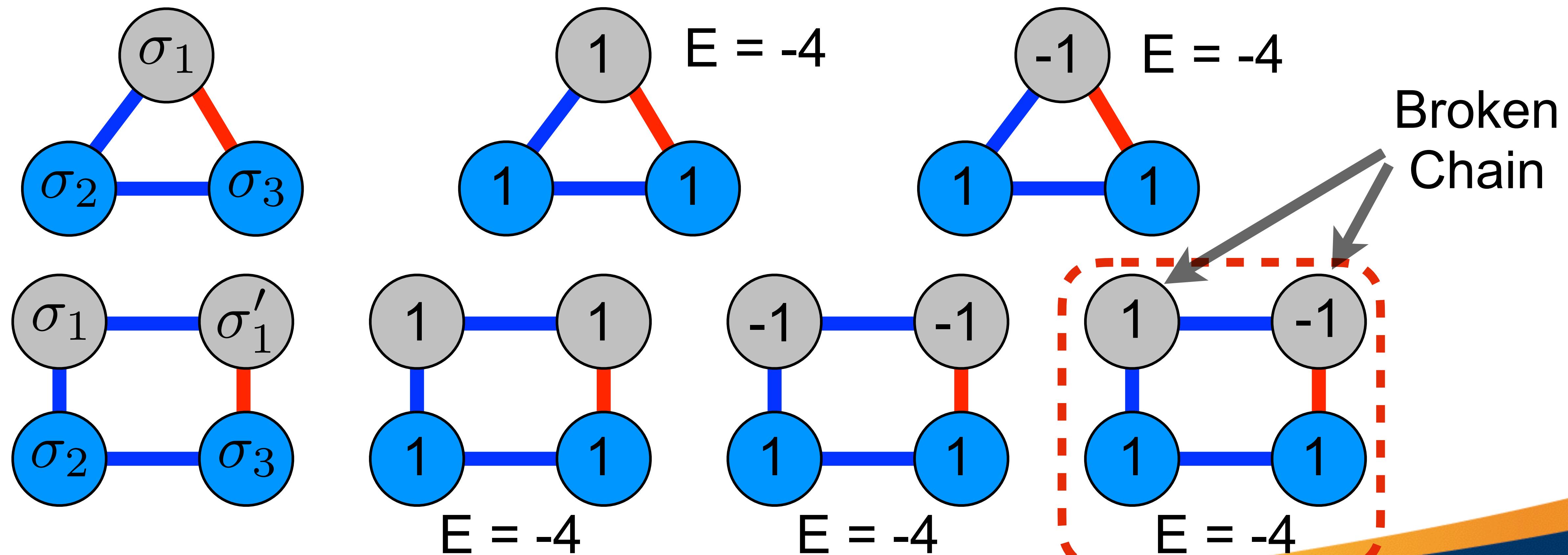


Frustrated Odd Cycle



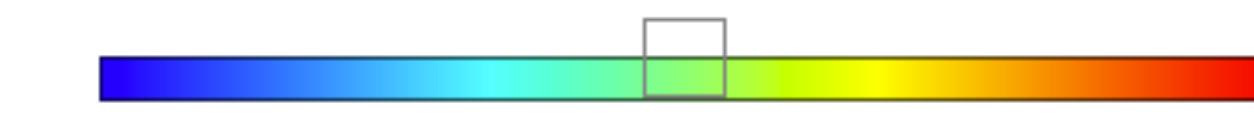
$$\sigma \in \{-1, 1\}$$

frustrated = no way to make all spins happy

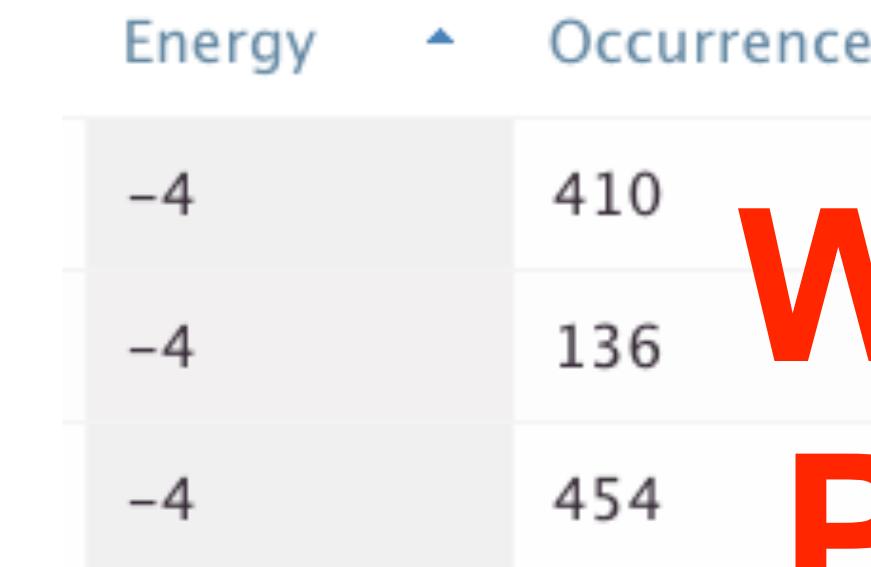
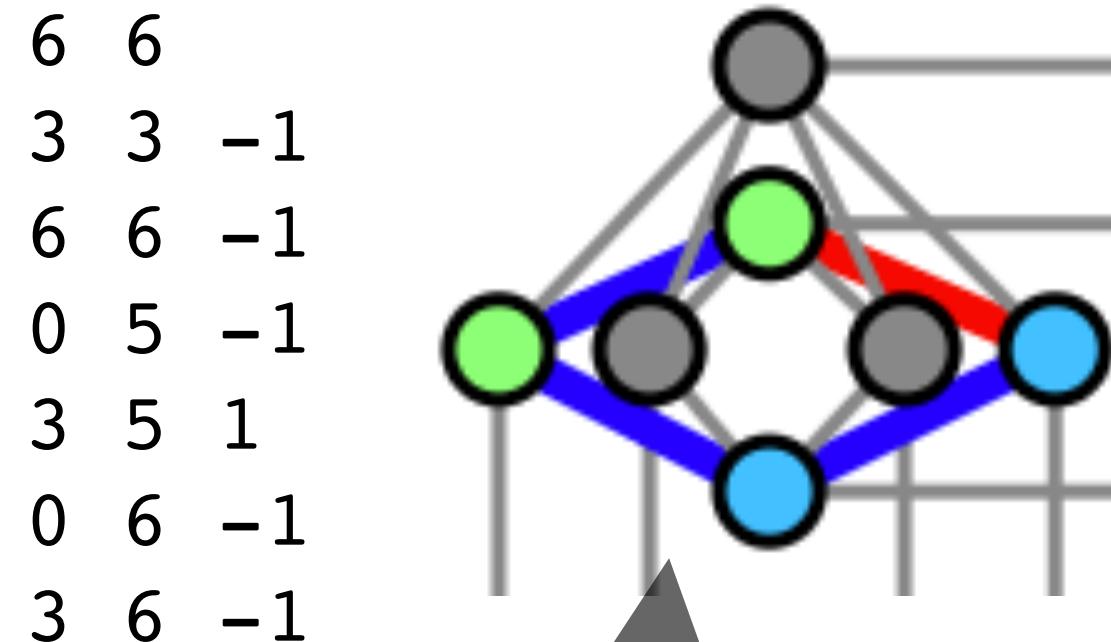


Frustrated Odd Cycle

$\sigma \in \{-1, 1\}$

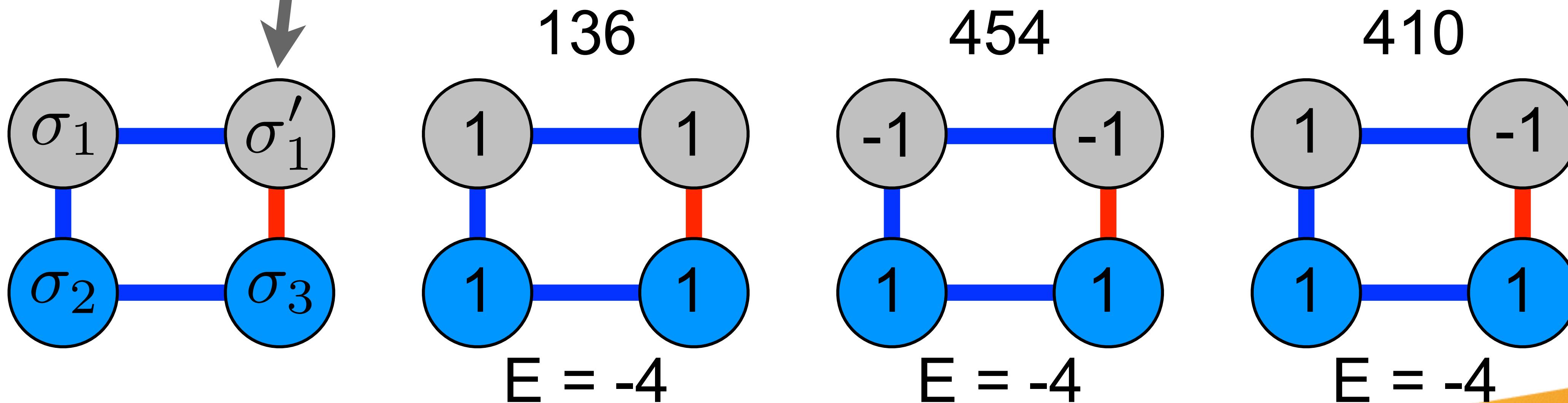


1000 Samples @ 20ms

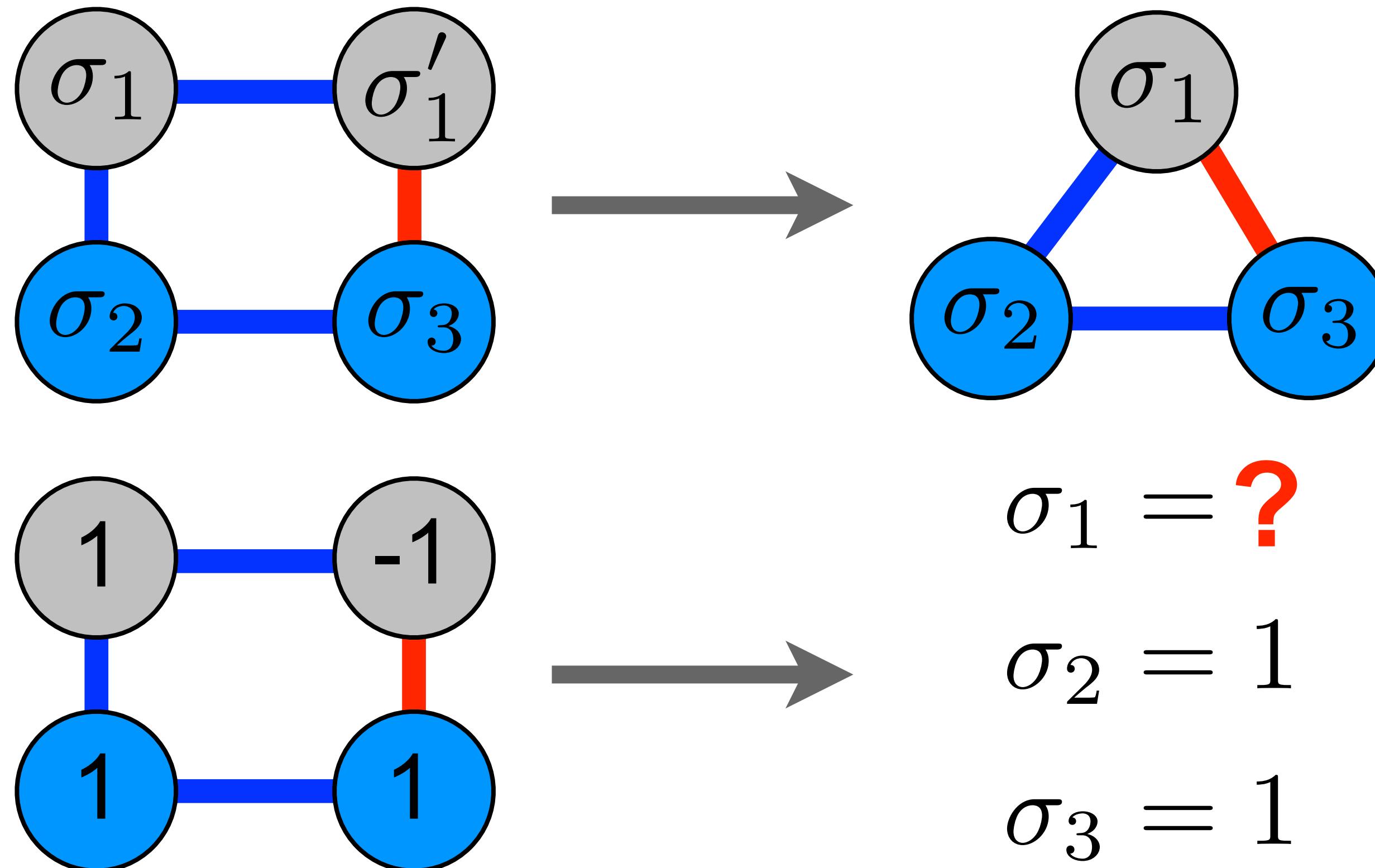
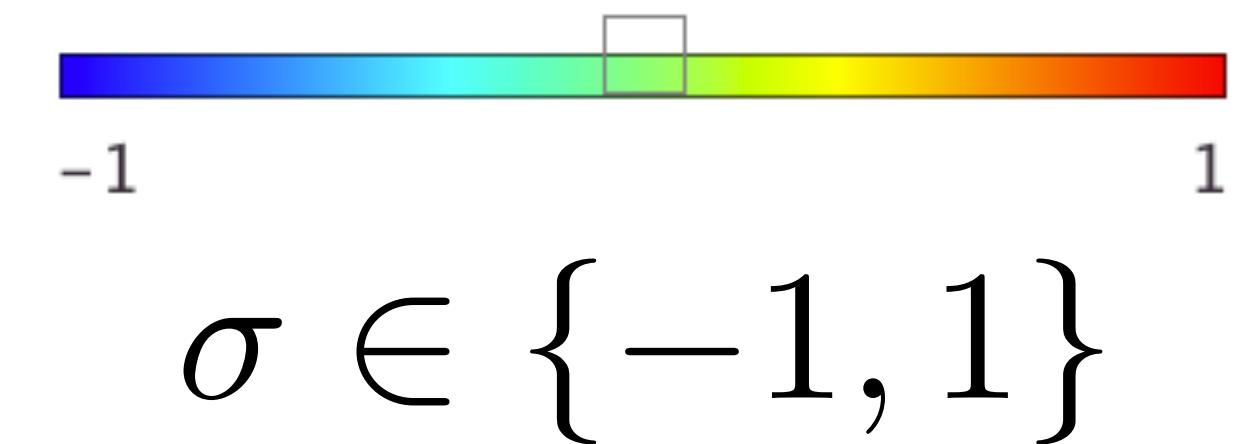


What's the Problem?

QPU is
“Chain Blind”



Solution Projection



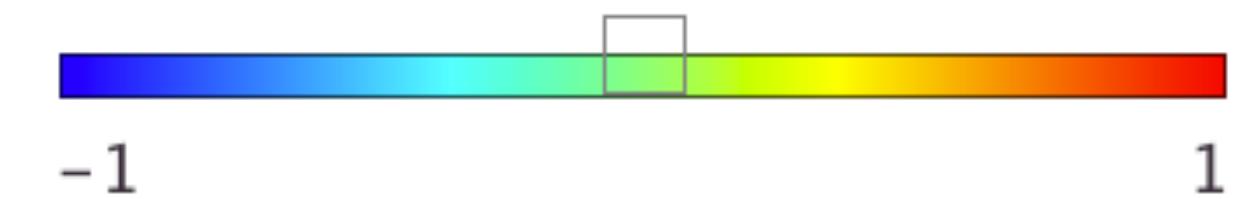
**The Challenge of
Broken Chains**

$$\sigma_1 = ?$$

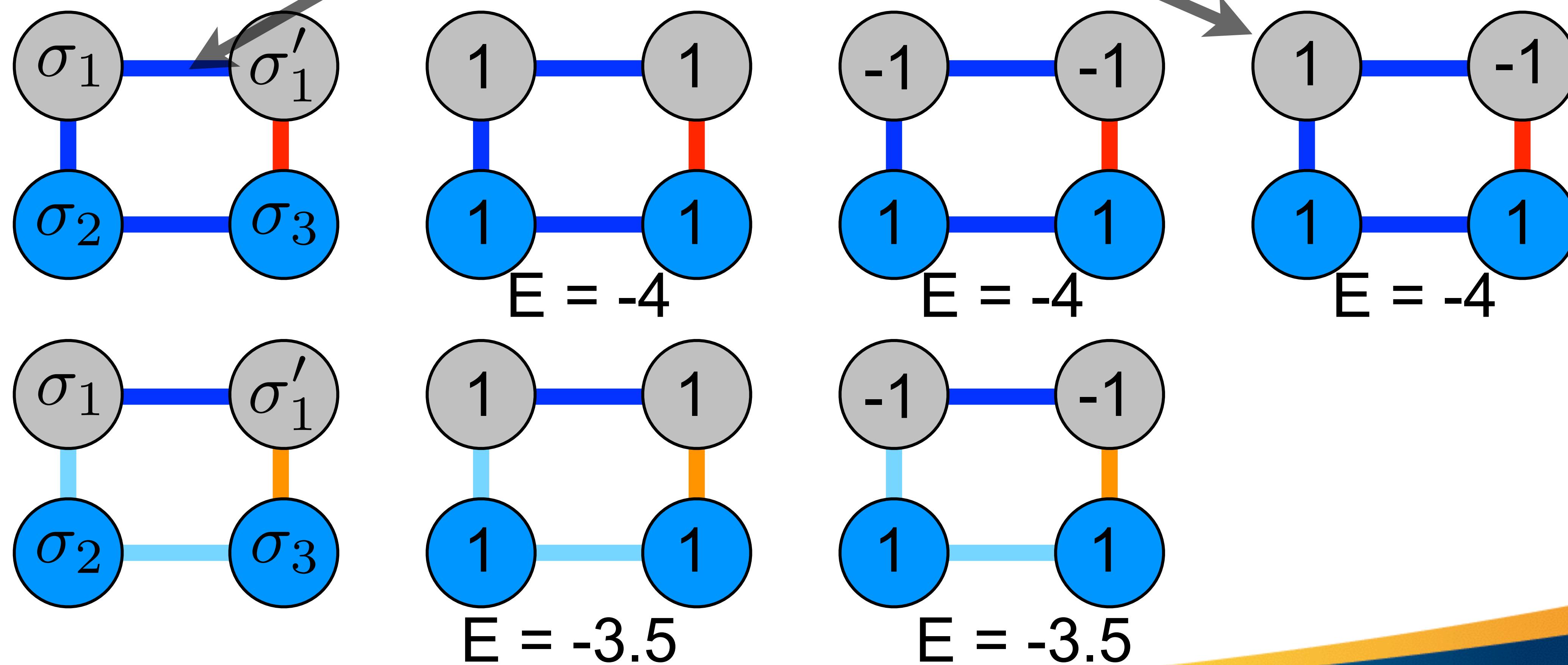
$$\sigma_2 = 1$$

$$\sigma_3 = 1$$

One Solution

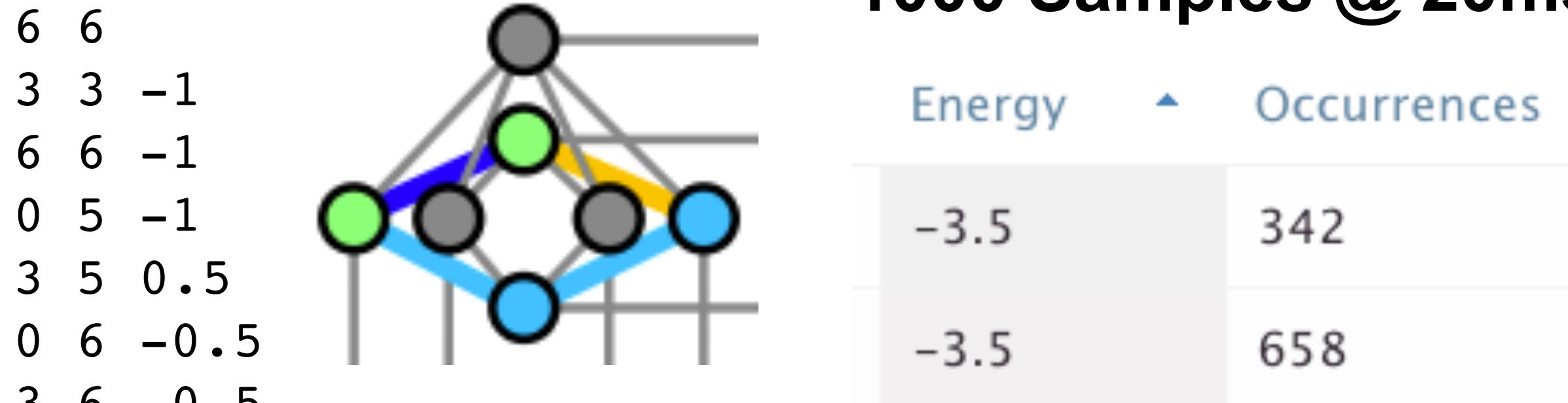


Increase Chain Strength
to Eliminate “Incorrect” Ground States



Frustrated Odd Cycle 2

1000 Samples @ 20ms



$\sigma \in \{-1, 1\}$

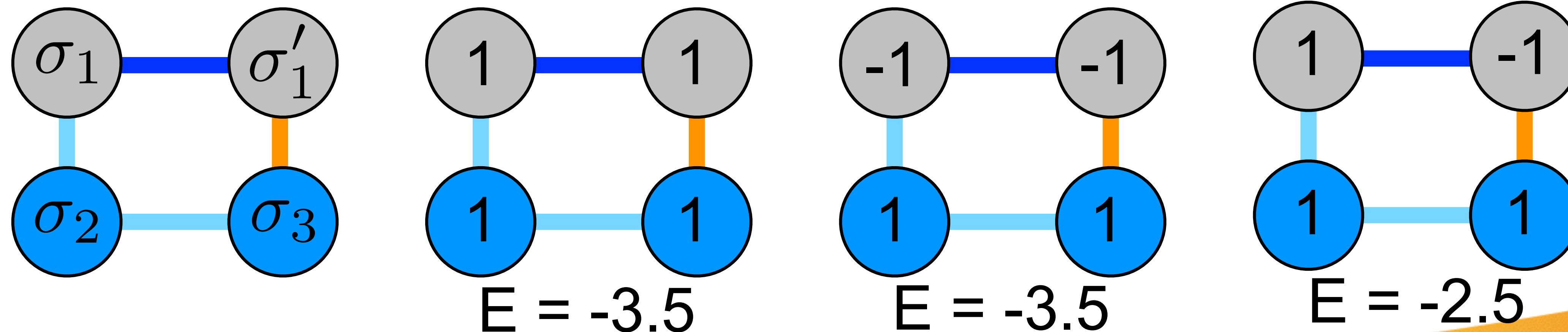
Problem
Solved!



342

658

0



Food for Thought:

**What are the implications of increased
chain strength on a boltzmann-like sampler?**

**What are the implications of longer chains
on a boltzmann-like sampler?**

Closing Recap

- D-Wave debugging is hard, focus on **super-small** tests
- D-Wave documentation talks a lot about **optimization**, but this does not match my experience
 - **Sampling** is a better mental model for me
- Take care with **chains** and setting the **chain strength parameter**
- **Test on the hardware** as much as possible, no one understands how to emulate it yet...

Good Luck!